DAIRY WASTEWATER TREATMENT USING SUBMERGED ANAEROBIC MEMBRANE BIOREACTOR

BY

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This thesis, written by **Gerardo Ramiro Aldana** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** in **Civil Engineering.**

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To my beloved family

- "there's no rainbow without rainstorm" -

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ABSTRACT

Name:	Gerardo Ramiro Aldana
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SAnMBRs are an attractive technology which needs further research efforts to efficiently reach to industrialization. Three different MLSS concentrations were tested, 5, 10 and 15 gr/l at four different OLR, 2000, 4000, 6000 and 8000 ppm COD working with synthetized dairy wastewater in a lab-scale bioreactor. At 15,000 mg/l of MLSS and 4000 ppm COD, maximum COD removal was achieved with a value of 91.4%, whereas at 2000 ppm COD maximum turbidity removal was obtained at 99.4%. Maximum biogas yield was obtained with 15,000 mg/l MLSS, with a value of 0.17 l/gr COD_r and a maximum methane content of 82%. Maximum phosphate removal efficiency was achieved at 5,000 mg/l MLSS and 2000 ppm COD with a value of 86.4%. During all the experiment turbidity removal was over 98%, increasing the removal with increasing MLSS. Kinetic coefficients obtained at 5,000, 10,000 and 15,000 mg/l MLSS were 0.2022, 0.2113 and 0.4270 mg/mg, 0.0022, 0.0014 and 0.0009 d^{-1}, 0.0334, 0.0615 and 0.1095 d^{-1}, and 6663, 5381 and 4612 mg COD/l for Y, k_d, μ_m and k_s, respectively. Values obtained from this work could be useful to design a pilot-scale treatment plant for dairy wastewater in anaerobic conditions.

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ملخص

الاسم: خيراردو راميرو الدانة

العنوان: معالجة المياه المهدرة من صناعة منتجات الألبان باستخدام

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تقنية "معالجة المياه المهدرة من صناعات الألبان باستخدام معامل حيوي بتقنية الفلترة اللاهوائية داخل الماء" هي تقنية مرغوبة تحتاج لجهود بحثية أكبر لتصل لمرحلة التصنيع بشكل أكثر فعالية. في هذه الرسالة تم اختبار ثلاث تركيزات MLSS. مختلفة 5, 10 و 15 جرام / ليتر، في أربع OLR, مختلفة 2000 و 4000 و 6000 و 8000 جزء من المليون COD المياه الصناعية المهدرة من صناعات الألبان والمنتجة بواسطة معامل حيوي في المختبر. عند قيمة 15000 ملغم/ل من MLSS و 4000 جزء من المليون من COD تم تحقيق القيمة العظمى لنزع COD بقيمة 91.4%، في حين عند 2000 جزء من المليون COD تم تحقيق تحقيق القيمة القصوى لإزالة الكدر بقيمة 99.4%. تم تحصيل الكمية القصوى من الغاز الحيوي أخذا بعين الاعتبار 15000 ملغم/ل MLSS، وقيمة 0.17 ل/جم COD بنسبة عظمى 82% من غاز الميثان. الكفائة القصوى لنزع الفوسفات تم تحقيقها عند 5000 ملغم/ل MLSS و2000 جزء من المليون COD بقيمة 86.4%. خلال التجارب المعملية، القيمة القصوى التي تم تحقيقها لإزالة العكر هي 98%، وتزيد النسبة بزيادة MLSS. المعاملات الحركية التي تم تحقيقها عند 5000، 10000 و15000 ملغم/ل MLSS هي 0.2022، 0.2113 و0.4270 ملغم/ملغم ، 0.0022 ،0.0014، و0.0009 يوم-1 ، 0.0334، 0.0615 و0.1095 يوم-1، و 6663، 5381 و4612 ملغم COD/ل لـ Ks ,µm, kd, Y .القيم التي تم جمعها خلال هذا البحث يمكن استخدامها لنموذج تجريبي أكبر لمحطة معالجة المياه المهدرة من صناعات الألبان في ظروف خالية من الهواء.

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CHAPTER 1

GENERAL DESCRIPTION

1.1 INTRODUCTION TO MEMBRANE BIOREACTORS

In the past few years anaerobic membrane bioreactor (AnMBR) technique has been considered a promising alternative for treating wastewater due to the many advantages over conventional aerobic treatment and aerobic membrane bioreactor (MBR) technique [B.Q. Liao, et. al. 2006, Y.J. Chan, et. al. 2009], being one of the major ones the energy production in the form of biogas and the possibility of high sludge retention times for a slow growth bacteria such as anaerobic ones.

Many researchers have thoroughly gone through the various potential applications of AnMBR in different stream treatment, as well as the fouling mechanism and how to control and minimize it. This arising in-development-stage new technology appears to be suitable for many streams, particularly for food industry wastewater and municipal wastewater. Notwithstanding this and its diverse advantages, it usually encounters more serious membrane fouling issues, which nowadays could not be targeted so far, according to the literature, with efficient success. However, several techniques of control or cleaning measures can be applied in order to remediate or counteract this limiting phenomenon.

Nowadays AnMBR status in the research community is on its optimization stage, where efficiency is the key parameter which will lead this attractive technology to stakeholders' hands. The biggest reason why it hasn't been widely industrialized is based upon low efficiency yielding, high costs regarding membrane replacement because of fouling issues, and high alkalinity requirement. Therefore, basically by improving the fouling control techniques, achieving a low fouling formation, will take this technology to a more efficient treatment which goes hand-by-hand with membrane replacement frequencies, and thus economics. However, to improve this, different configurations of OLR have to be tested.

CHAPTER 2

BIOREACTOR FUNDAMENTALS

2.1 BACKGROUND INTRODUCTION

The anaerobic digestion is defined as the breakdown of organic material by a microbial community in an oxygen free media. Within this process methane and carbon dioxide gas are being produced at a rate that will depend on several factors, amongst them pH, temperature shocks, and others. This gas produced, called “biogas”, can be used to produce electricity and heat, and in several cases is being used for sparging the gas under the membranes in the case of submerged conditions. The conversion of solids to biogas reduces the amount of solids to be further treated and disposed, thus posing the anaerobic technology over aerobic conditions. During the anaerobic process several compounds are converted and biodegraded: organic nitrogen is converted to ammonia, sulfur compounds to hydrogen sulfide gas, phosphorous to orthophosphates, and calcium, sodium and traces of other metals are converted to salts. Thus, the end products of the anaerobic process are natural gas (methane), a nutrient rich sludge (whose proper operation can bring about a variety of beneficial commercial products), and other saleable inorganic products.

This process is one of the most important used for treating many industrial and municipal wastewaters because it joins together pollution reduction with energy

production. Furthermore, its operation costs are substantially lower than conventional aerobic systems, due to that aeration with oxygen is not needed and sludge production is lower. However, it has not reached the widespread use mostly due to the biomass retention and membrane fouling issues, being the former the most important aspect of an anaerobic technology in conventional and non-conventional anaerobic treatment.

In the past 30 years the use of membranes has been well established in aerobic biological waste processes. With this new technology a complete sludge retention within the bioreactor can be achieved with the use of membranes in the range of microfiltration (MF) or ultrafiltration (UF). Moreover, it offers reduced footprint, capacity to handle fluctuations in the influent quality, and better effluent quality with high efficiencies. This process then, as it worked perfectly fine in the aerobic system, was applied to the anaerobic system. The latter is of interest due to the fact that it depends on the retention of a large microorganism's community with low growth.

In this way, if working at anaerobic conditions the advantages of MBRs could be enhanced [B.Q. Liao, et. al. 2006, Y.J. Chan, et. al. 2009]. The principal disadvantage of this type of MBRs, whereas anaerobic or aerobic, is the fouling of the membrane, because it reduces the membrane permeate fluxes, increases the costs and does not let MBRs to be economically competitive [S.F. Aquino, et. al. 2006].

2.2 ADVANTAGES AND DISADVANTAGES

Anaerobic microorganisms are well known to grow and reproduce at a very low rate [Y.J. Chan, et. al. 2009], thus putting biomass retention in a crucial position for anaerobic wastewater treatment when working at high-rate. Biofilm and granule based

technologies, like PAC or GAC [Aurangzeb Akram (a), et. al. 2008], are commonly used in order to achieve the required sludge retention aiming to operate a bioreactor with more biomass, thus higher organic loading rates (OLR) [D. Jeison (a), et. al. 2008]. Nevertheless under certain conditions of thermophilic temperatures or high salinities, granule and biofilm systems present negative results and modified performance. For this reason is that AnMBRs can be applied in order to attain the required SRT [D. Jeison (a), et. al. 2008] in non-conventional conditions like the named before. This technology can be successfully operated at longer SRTs [W. Fuchs, et. al. 2003], improving the retention of all the microorganisms within the bioreactor, giving them the opportunity to become fully grown and substantially enhancing the anaerobic treatment [F. Meng, et. al. 2007].

AnMBR systems are primarily used upon two different configurations: external-side stream and submerged configurations. In general, the first one provides a better hydrodynamic fouling control, an easier replacement of the membrane and higher permeate fluxes. Nevertheless it demands higher cleaning frequency and has an energy uptake in the order of 10 KWh/m3 of product [P. Le-Clech, et. al. 2006]. Furthermore, the biomass activity is negatively affected at high cross-flow velocities [M. Brockmann, et. al. 1996, K.-H. Choo, et. al. 1996, W.R. Ghyoot, et. al. 1997]. On the other hand, submerged conditions mean the membrane is directly placed into the bioreactor and with the help of a pump or gravity the permeate is dragged through the membrane. Results showed a decrease in energy uptake and in cleaning frequency, and because its cross-flow velocities are lower, an improvement in the operational conditions.

On one hand, the main positive points in the application of AnMBRs are related mainly to energy and sludge production, as well as to treatment of several pollutants and space requirements. Anaerobic processes are energy producers rather than users, as it is the case for aerobic processes. The energy produced takes into account methane production as a prospective solution to increase wastewater temperature to mesophilic temperature range, for example. By doing this, the methane production will increase abruptly based on the bacteria consortia that will grow faster than in the psychrophilic range of temperature. Nevertheless, compared to aerobic system, this process result in lower sludge production by a factor of 6 to 8 times, lowering sludge processing and disposal costs. Furthermore these bacteria consortia, though with a low growth rate, need fewer nutrients than in the aerobic process, resulting in a final reactor size much smaller with space saving.

On the other hand, the drawbacks of this kind of systems mainly reside in its sensitiveness to changes in the working environment, such as temperature or toxic compounds shocks, and the most important fouling of the membrane. Moreover, as it has a low bacteria growth rate, it needs longer start-up time to develop the necessary biomass population, which at the same time is composed by four different types of bacteria. Finally, due to the lack of pH fluctuation acceptance by the bacteria, alkalinity may be needed to be added in order to keep an acceptable pH environment and continue with the methanogen bacteria growth, or else the production of methane could be abruptly stopped. Therefore, the optimum pH for anaerobic process is in the range 6.5-8.5 with the best performance at 6.8-7.5, with more methane production in the higher mesophilic temperature range (35°C).

Membrane fouling is usually prevented applying shear forces over the membrane surface. In side-stream MBRs is regularly done by high cross-flow velocities application, whereas for submerged conditions gas sparging was found to be the conventional way to reproduce this shear conditions making use of the produced biogas, though also back-flush is a common technique applied for controlling fouling in the membranes.

2.3 MEMBRANE MATERIALS AND MODULES

Polymeric, metallic and inorganic (ceramic) materials are the most widely used for membranes. It is possible to effectively backwash the ceramic membranes enhancing corrosion, abrasion and fouling resistances [C.B. Ersu, et. al. 2008, R.W. Baker, et. al. 2000]. It was reported that a commercial ceramic membrane operating in the MF range has reached a flux of 200-250 l/m^2hr [W.R. Ghyoot, et. al. 1997], 10 times more than that reached with a polymer membrane in UF range, producing both of them close permeate quality when filtrating anaerobic sludge. For this reason is that ceramic membranes were the most used at the initial phases of AnMBR investigations [W.R. Ghyoot, et. al. 1997, T. Imasaka, et. al. 1989, I.S. Chang, et. al. 1994, A. Beaubien, et. al. 1996]. On the other hand, metallic membranes were also tested and studied in AnMBR systems, and if compared to polymeric membranes, these show a faster fouling recovery, better resistance to the impact force, improved hydraulic performance, and high temperature and oxidation resistances [S. Zhang, et. al. 2005, J.O. Kim, et. al. 2007]. Even though all these advantages and positive improvements, ceramic and metallic membranes costs are much higher than polymeric's, thus gaining the latter the interest of the market in general.

There are two different polymeric membrane materials that are used in the market: polyvinylidene difluoride (PVDF) and polyethersulfone (PES), representing 75% of the products on the market [A. Santos, et. al. 2010]. There are several other materials that can be used for AnMBR applications.

The membranes modules that AnMBRs use are mainly accomplished by using membranes in the range of MF and UF. There are three different types of configuration that will depend on the needs and the bioreactor's design: hollow fiber, flat sheet and tubular. The most used ones in SMBRs are the hollow fiber membranes because of their cost efficiency and high packing density. Nevertheless, flat sheet membrane modules also caught the attention of specially the research community for many reasons like easy defective membranes replacement, easy cleaning and better stability, [H.J. Lin, et. al. 2009, J. Kim, et. al. 2007, E. Kocadagistan, et. al. 2007, H. Lin (a), et. al. 2011, M. Kanai, et. al. 2010]. On the other hand, a tubular membrane module, constructed in a tube-rack, has several advantages like easy to clean, low fouling, simple to handle SS and fluids with high viscosity, and the easy replacement of a damaged membrane. However, it includes disadvantages like elevated costs for the invested capital and pumping, moderate density of packing and high dead volume [M. Herrera-Robledo, et. al. 2010, J. Zhang, et. al. 2007, A. Torres, et. al. 2011, K. Stamatelatou, et. al. 2009, A. Pierkiel, et. al. 2005]. In general the pore size for the membranes ranges from 0.03-1 μm, which is certainly smaller than the size of the majority of the microorganisms or flocs in AnMBRs, thus achieving a fairly complete biomass retention.

2.4 TREATMENT METHODS APPLIED IN SAUDI ARABIA

Since the oil industry has started developing since 1933, the population started to concentrate in big towns and cities in search of jobs. Right after the Second World War the oil related companies had a quick expansion, fostering Saudi Arabia's population to grow as fast. Nowadays Saudi Arabia population is around 29 millions, including around 7 millions of non-nationals, and Riyadh, the capital, is one of the three biggest cities in the country.

Not only the population grew fast, but also the milk and dairy products demand. Thus, the Government's policies targeted to a self-sufficiency goal of dairy products.

Since 1973 Saudi Arabia's Government has encouraged to apply modern technology in farms. These efforts increased the production of bovine milk from 166 millions liters in 1986 to 510 millions liters in 1997, reaching a record of 729.4 millions liters by 2012. These numbers keep increasing at a rate of 6%/year in Saudi Arabia and the production has to keep its pace. The consumption of milk in Saudi Arabia is 24.6 liters per capita, and is considered low when compared to the 120 liters per capita of the global average.

Nowadays, Saudi Arabia has a 61% share domination of the GCC's dairy market, and the health-concious community that demands dairy products is increasing day by day, thus helping to strength more the market. (Al-bawaba news)

All this leads to an immense consumption of water by the dairy companies, who are trying to cover the non-stop increasing demand of dairy products, mainly fresh milk and laban. In average, a dairy factory has a water intake of approximately 1.3 – 2.5

ltrs. / ltr. of milk (UNEP, 2002), which cannot be disposed directly to the sewage system, nor to any water body (the Persian Gulf or the Red Sea, in the case of Saudi Arabia). This means that an average of 1.9 ltrs. water / ltr. of milk are being disposed, leading to a total of around 1385.9 million liters of wastewater (0.195% of total wastewater generated in Saudi Arabia - 710,000 million liters/yr; Global Water Intelligence, 2011), that has to be treated annually, not to mention that the methodology applied would make a huge difference if economics and environmental issues are on the bet.

More than 38 different dairy factories constitute the dairy industry in Saudi Arabia, with the majority of them in Riyadh (16), around 14 in the Eastern Province, 8 in the west, and the rest spread across the country. The main producers offering grand quantities of commercial dairy products are Al-Safi, Al-Matrood, NADEC, Almarai, Al-Hana, Aziziah, Al-Othman and Najdyah.

Al-Marai applies WETICO solutions by using Membrane bioreactors flat sheet technology and tertiary treatment to meet stringent effluent quality (5 ppm BOD and TSS). This high quality effluent water with less than 5 ppm BOD and 5 ppm TSS, can be used for unrestricted irrigation purposes. The equipment and units that form part of this facility include: Preliminary screening and grit removal, anoxic treatment, balancing system, aerobic treatment, MBR system, chemical treatment for pH adjustments and disinfection.

Whereas Al-Safi is another grand dairy farm located in Al-Kharj, with nearly 3500 hectares of land (recognized in 1998 by the Guinness World Book of Records as the

largest integrated dairy farm in the world), has a treatment plant consisting of primary-secondary screen unit, equalization tanks, primary sedimentation, dissolved air unit, extended aeration to treat the activated sludge, final sedimentation unit, sand filtration and final disinfection.

Both above mentioned dairy factories implemented biological systems as part of their wastewater treatment method. Nonetheless, they are utilizing an aerobic system, which consumes much energy and land space for the different installations, and get the same results as if they were making use of an anaerobic system with the advantage of occupying much less land space and operating at higher flow rates. Despite the fact that the company is already working, the pipelines are already installed and the system is running, the implementation and innovation towards a better technology like the Submerged Anaerobic Membrane Bioreactor (SAnMBR) would not induce to further modifications. In fact, the SAnMBR can be easily installed in the wastewater stream without stopping any activities. As said hereinbefore, the main advantages of this system are the energy production instead of consumption, and the land space occupied by the establishment.

This promising technology in development stage has been particularly studied the last two decades, and mainly researchers have focused in the past decade on explaining its major advantages and drawbacks, thus trying to improve some of its drawbacks like membrane fouling. Nevertheless, fouling control has not been fully accomplished yet nor understood in lab-scale experiments. Therefore the need for further investigation regarding the matter, as the technology offers many energy saving benefits and even the production of it, plus it can treat, with the proper operation and control, high

strength wastewaters, as the industrials' are, and as some dairy wastewaters are. Finally, studies regarding the application of SAnMBRs in the treatment of dairy wastewater are scarce and confront the problem of pH destabilization, temperature and organic loading rate shocks, and membrane rapid fouling.

This thesis project will be focused in the stabilization of the bacteria consortia, taking into account membrane fouling control studies, in order to get an acceptable permeate regarding COD and Phosphate concentrations, as well as measuring the biogas obtained, the gas yield, turbidity and biokinetics of the system.

CHAPTER 3

THEORETICAL APPROACH

3.1 BACTERIAL CONSORTIA

Hydrolitic, acidogenic, acetogenic and methanogenic bacteria are the four different types of metabolic bacteria that interact and work together in anaerobic digestion in order to degrade organic compounds into carbon dioxide (CO_2) and methane (CH_4).

In order to produce methane, the bacteria responsible for that has to live within an environment where pH fluctuates from 6.5 to 8.5, that is in a neutral to alkaline media. Methane producing bacteria have a very low growth rate compared to acid forming bacteria, thus the need to control them because if the acid producing bacteria grow too fast they can produce more acid than what the methanogenic bacteria can actually consume. This will lead to an excess of acid in the system, drop in the pH and system instability, inhibiting the activity of methanogenic bacteria up to the point of bringing methane production to a halt. If a large quantity of methanogenic bacteria is active, pH can be easily controlled and stabilized. Thus, systems with sludge retention technology are more stable than systems based in bacterial growth.

3.2 ANAEROBIC FERMENTATION AND OXIDATION

In a wastewater treatment system, under anaerobic conditions, the sludge produced releases gases called “biogas”, which can be used as an energy source. Three different types of methane producing bacteria can be active within a bioreactor, depending on its temperature range:

- psychrophilic bacteria from 10 – 20°C, optimum 20°C

- mesophilic bacteria from 20 – 42°C, optimum 35°C

- thermophilic bacteria from 45 – 65°C, optimum 60-62°C

In order to produce biogas this bacteria consortia need a stable environment, because it is sensitive to fluctuations in pH, flux, SRT and temperature, among others. This community includes the bacterial consortia with complex interactions during all the degradation process.

3.2.1 Anaerobic degradation description

There are basically three phases during the anaerobic degradation of wastewater. The first step is *hydrolysis*, which involves the participation of hydrolytic bacteria. Coarse particles are broken down to soluble compounds so they can be further converted by hydrolysis to simple monomers, which are then used by fermentative bacteria. Macro-molecules and polymers like proteins, lipids or polysaccharides, are hydrolyzed to simpler monomers like alcohol, fatty acids or amino acids, by a specific kind of microorganism that releases an enzyme capable of doing the hydrolysis.

Acidogenic bacteria keeps breaking down the monomers produced in the previous phase, thus this second phase is *fermentation* or acidogenesis. In this phase, sugars and amino acids are broken down as well as some VFAs. The main products of this phase are hydrogen, acetate, CO_2, butyrate and propionate. The autotrophic acetogenic bacteria assimilates the propionate, butyrate and other VFAs and alcohols to produce more acetate, hydrogen and CO_2. This phase is called *acetogenesis*, and the final products of fermentation are the precursors of methane formation (*methanogenesis*).

The last phase, *methanogenesis*, is carried out by methanogenic bacteria. Acetogenic bacteria also use CO_2 oxidizing hydrogen and forming more acetic acid, but the latter is used to produce methane. In anaerobic digestion, the methane produced by acetate accounts for more than the 72%. The slowest kinetics in anaerobic digestion are during the hydrolysis phase, thus this is the limiting step. Methanogenics and acidogenics present a mutual-helping relationship where the former uses fermentation end products like acetate, formate and hydrogen to break them down into CO_2 and CH_4. This process where hydrogen is produced by acidogenics and used by methanogenics, is called *interspecies hydrogen transfer*. During the methanogenesis the partial pressure of hydrogen is kept so low that it fosters the formation of more oxidized end products by shifting the fermentation phase equilibrium.

3.2.2 Stoichiometry and gas composition

There is a limited number of compounds that can be used by the methanogenic bacteria. There are two types of reactions defined as CO_2 group type reactions, which include the oxidation of hydrogen and CO, and methyl group type reactions, which

include the oxidation of methanol, acetic acid, methylamine and formic acid [Madigan M. T., et. al. 1997], as shown below:

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

$4HCOO^- + 4H^+ \rightarrow CH_4 + 3CO_2 + 2H_2O$

$4CO + 2H_2O \rightarrow CH_4 + 3CO_2$

$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$

$4(CH_3)_3N + H_2O \rightarrow 9CH_4 + 3CO_2 + 6H_2O + 4NH_3$

$CH_3COOH \rightarrow CH_4 + CO_2$

To measure the COD concentration's reduction in the fermentation process a COD balance can be applied where, instead of taking into account the oxygen used for reducing the COD, the COD removal is accounted for the methane produced. Therefore the COD accounted for CH_4 production will be the amount of O_2 that has been used in the oxidation of methane to $CO_2 + H_2O$: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.

Considering our case of mesophilic temperature conditions, around 25°C, the volume of CH_4 produced per gram of COD removed would be:

According to Henry's gas law: $V = \frac{nRT}{P} = \frac{1 mole x 0.082057 \frac{atm.L}{mole.K} x (273+25)}{1 atm.} = 24.453 L$

COD in one mole of methane equals to 64 gr, then for anaerobic conditions the quantity of CH_4 produced at 25°C is equal to 0.382 L CH_4/gr COD_r. According to

different literature, the general composition of the biogas obtained under anaerobic conditions is shown in Table 3.1.

3.3 DAIRY INDUSTRY WASTEWATER

Dairy wastes can be treated by anaerobic digestion as Figure 3.1 shows, where there are two different waste streams. One comes from the confinement area and the other directly from the parlor. The characteristics of these wastes will be dependent upon many factors such as the manure transport if any and its treatment, the type of bedding, and others.

Introducing screening and sedimentation steps in the process could reduce the amount of solid organics that could be converted to biogas in the bioreactor. On the other hand, absence of silt and sand could solve problems like forced equipment, clogged pipes, and would reduce the volume of the tanks, enhancing the process speed. In this matter sand presents a problem when treating thick slurries instead of dilute wastewater because it precipitates inside the bioreactor after the break down of the organics into biogas, when the solids concentration diminishes, unless intense mixing is applied to keep solids in suspension. In case the concentration of sand is moderate to low, it can bypass the screening and sedimentation tank being directly discharged into the bioreactor. Dairy wastewater characteristics will depend on the process being held on the facility, the amount of water used for washing, the type of detergents utilized, type of bedding used, dairy end products elaborated and cleaning frequencies. Regarding this aspect dairy wastewater will eventually vary but will remain within a certain range as published by Wang & Howard in Table 3.2, Table 3.3 and Table 3.4.

Compound	Average concentration (%)
CH_4	55-90
CO_2	25-45
H_2S	0.01-1
N_2	2-6
H_2	0.1-2

Table 3.1 Biogas composition under anaerobic processes

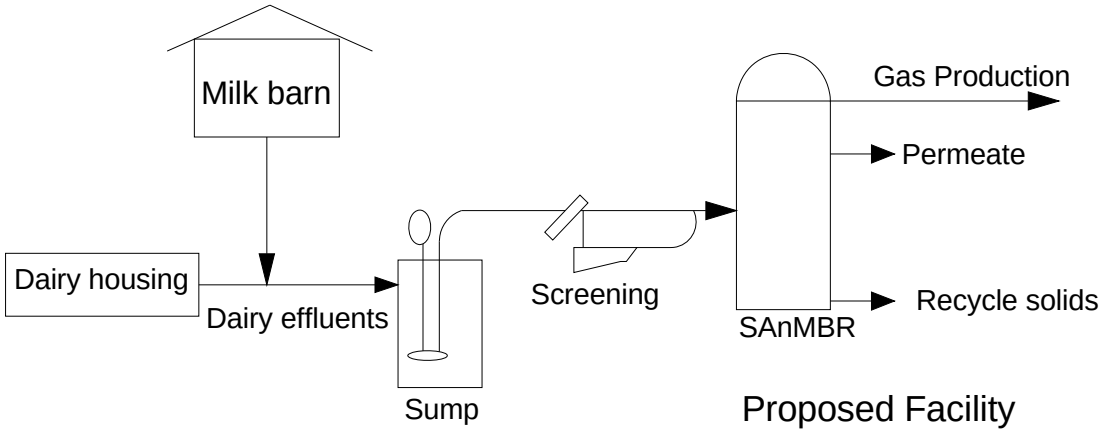

Figure 3.1 Integration of SAnMBR in Dairy wastewater Stream

COD	BOD	Fats	TN	TP	pH	TS	VS	TSS	VSS
4000	2160	NP	200	60	5-9	5100	4300	NP	500
2926	1580	294	36	21	6.7	2750	1880	NP	NP
633	260	NP	106	NP	8.9	710	447	240	NP
2209	1112	60	NP	NP	7.2	NP	NP	278	NP
4500	2300	NP	56	33	7.2	2540	1093	716	NP
3190	1950	690	43	7	5-10	NP	NP	820	NP
4000	2600	400	55	35	8-11	-	-	675	635

Composition in mg/l with the exception of pH; NP: not published.

Table 3.2 Characterization of global effluents from 7 dairy industries [F. Carta-Escobar, et. al. 2004]

Industry	BOD_5 mg/l	COD mg/l	pH	FOG g/l	TS mg/l	TSS mg/l	Alkalinity mg/l as $CaCO_3$	Ref.
Cheese								
14 Cheese/Whey plant	565-5722	785-7619	6,2-11,3	-	1837-14205	326-3560	225-1550	[1]
Cheese/Whey plant	377-2214	189-6219	5,2	-	-	188-2330	-	[2]
Cheese factory	-	5340	5,22	-	4210	-	355	[3]
Cheese factory	-	2830	4,99	-	-	-	-	[4]
Cheese	588-5000	1000-7500	5.5-9.5	-	-	500-2500	-	[5]
Cheese processing Industry	-	63300	3,38	2,6	53200	12500	-	[6]
Cheese	-	-	4.7	-	-	2500	-	[7]
Cheese/Casein plant	-	5380	6,5	0,32	-	-	-	[8]
Cheese/Casein plant	8000	-	4,5-6	0,4	-	-	-	[9]
Cheese factory (Turkey)	483-6080	921-9004	5,52-5,78	142-400	-	134-804	-	[10]
Milk								
Milk processing plant	-	713-1410	7,1-8,1	-	900-1470	360-920	-	[11]
Milk/yogurt plant	-	4656	6,92	-	2750	-	546	[12, 3]
Milk/cream bottling plant	1200-4000	2000-6000	8-11	3-5	-	350-1000	150-300	[12, 13, 14]
Fluid milk	500-1300	950-2400	5.0-9.5	-	-	90-450	-	[15]
Butter/milk powder								
Butter/milk powder plant	-	1908	5,8	-	1720	-	532	[3]
Butter/milk powder plant	1500	-	10-11	0,4	-	-	-	[8]
Butter/Comte cheese plant	1250	2520	5-7	-	-	-	-	[13]
Whey								
Whey wastewater	35000	-	4,6	0,8	-	-	-	[8]
Raw cheese whey	-	68814	-	-	3190	1300	-	[16, 17]
Raw cheese whey (Tunisia)	34870-40550	65300-71900	4,6-5,17	8,3-10,6	5,93%	1350	-	[18]
Cheese whey	-	61000	-	-	-	1780	-	[19]
Multiproduct plant								
Mixed dairy processing	-	63100	3,35	-	53000	12500	-	[20]
Mixed dairy processing	-	1150-9200	6-11	-	2705-3715	340-1730	320-970	[21]

Industry	BOD_5 mg/l	COD mg/l	pH	FOG g/l	TS mg/l	TSS mg/l	Alkalinity mg/l as $CaCO_3$	Ref.
Multiproduct plant								
Dairy factory	260-3000	633-4500	5-11	60-754	710-5100	191-1100	-	[22-32]
Milk reception	-	814-2774	8.46-11.66	0,148-0,358	-	-	-	[33]
Fluid products	-	1473-3067	5.93-13.31	0,178-0,868	-	-	-	[33]
Dry products	-	463-4319	7.56-13.3	0,130-0,463	-	-	-	[33]
Raw wastewater	-	1265-3717	8.68-12.22	0,069-0,505	-	-	-	[33]
Others								
Not defined	680-4500	980-7500	-	-	-	300	-	[34]
Not defined	-	-	4.7	-	-	90-450	-	[35]

[1] A. Akram (a), et. al. 2008, [2] P.J. Van Zyl, et. al. 2008, [3] M. Kanai, et. al. 2010, [4] A. Akram (b), et. al. 2008, [5] A. Saddoud (a), et. al.2007, [6] D. Jeison (a), et. al. 2008, [7] N. Brown, et. al. 2006, [8] W. Fuchs, et. al. 2003, [9] F. Meng, et. al. 2007, [10] S. Zhang, et. al. 2005, [11] P. Le-Clech, et. al. 2006, [12] M. Brockmann, et. al. 1996, [13] K.-H. Choo, et. al. 1996, [14] J. Zhang, et. al. 2007, [15] D. Martinez-Sosa, et. al. 2011, [16] W.R. Ghyoot, et. al. 1997, [17] P.M. Sutton, et. al. 2010, [18] H. Lin (a), et. al. 2011, [19] J. Ho, et. al. 2009, [20] A. Saddoud (b), et. al.2007, [21] A. Pierkiel, et. al. 2005, [22] Y. Chen, et. al. 2008, [23] W.J.J. Gao, et. al. 2010, [24] K. Xie, et. al. 2010, [25] W.J. Gao, et. al. 2011, [26] P. Weiland, et. al. 2010, [27] C.A. de Lemos Chernicharo, et. al. 2007, [28] A. Akram (c), et. al. 2008, [29] A.Y. Hu, et. al. 2006, [30] E. Kocadagistan, et. al. 2007, [31] T. Wang, et. al. 2009, [32] J. Ho, S et. al. 2010, [33] I.S. Chang, et. al. 1994, [34] K. Stamatelatou, et. al. 2009, [35] A.Y. Hu, et. al. 2006.

Table 3.3 Chemical characteristics of different dairy plant wastewaters.

Industry	Total P mg/l	PO_4-P mg/l	TKN mg/l	NH_4-N g/l	Na^+	K^+	Ca^{2+}	Mg^{2+}	Ref.
Cheese									
14 Cheese/Whey plant	29-181	6-35	14-140	1-34	263-1265	8,6-155,5	1,4-58	6,5-46	[1]
Cheese/Whey plant	0,2-48	0,2-7,9	13-172	0,7-28,5	-	-	-	-	[2]
Cheese factory	45	-	102	-	550	140	30	35	[3]
Cheese	280	-	830		-	-	-	-	[4]
Cheese	-	-	-	-	720-980	-	530-950	-	[5]
Cheese/Casein plant	100	-	200	-	380	160	95	14	[6]
Cheese/Casein plant	85	-	140	-	410	125	70	12	[3]

Industry	Total P mg/l	PO_4-P mg/l	TKN mg/l	NH_4-N g/l	Na^+	K^+	Ca^{2+}	Mg^{2+}	Ref.
Cheese factory (Turkey)	9-111,5	-	8-230	2,5-91	-	-	-	-	[7]
Cheese/whey-alcohol-beverages	-	-	-	-	419-735	8-43	33-54	8,3-17	[8]
Milk									
Milk/cream bottling plant	-	20-50	50-60	-	170-200	35-40	35-40	5-8	[9, 10, 11]
Butter/milk powder									
Butter/milk powder plant	35	-	70	-	560	13	8	1	[6]
Butter/ cheese plant	50	-	66	-	-	-	-	-	[12]
Whey									
Whey wastewater	640	-	1400	-	430	1500	100	17	[6]
Raw cheese whey	379	327	1462	64,3	-	-	-	22	[13, 14]
Raw cheese whey (Tunisia)	500	-	1120	-	-	-	-	-	[15]
Cheese whey	510	-	980	-	-	-	-	-	[16]
Multiproduct plant									
Dairy factory	7-100	-	18-296	-	-	-	-	-	[17-27]
Mixed dairy processing	8-68	-	14-272	-	123-2324	8-160	12-120	2-97	[28]
Milk reception	11-39,4	-	20,7-69,9	-	-	-	-	-	[29]
Fluid products	21-63,2	-	32,5-109,9	-	-	-	-	-	[29]
Dry products	16,1-94	-	15,3-161	-	-	-	-	-	[29]
Raw wastewater	16,4-58,6	-	23-116	-	-	-	-	-	[29]

[1] D. Jeison (a), et. al. 2008, [2] P.J. Van Zyl, et. al. 2008, [3] A. Akram (b), et. al. 2008, [4] N. Brown, et. al. 2006, [5] A. Saddoud (a), et. al.2007, [6] W. Fuchs, et. al. 2003, [7] S. Zhang, et. al. 2005, [8] A. Torres, et. al. 2011, [9] P. Le-Clech, et. al. 2006, [10] M. Brockmann, et. al. 1996, [11] J. Zhang, et. al. 2007, [12] K.-H. Choo, et. al. 1996, [13] W.R. Ghyoot, et. al. 1997, [14] P.M. Sutton, et. al. 2010, [15] H. Lin (a), et. al. 2011, [16] J. Ho, et. al. 2009, [17] Y. Chen, et. al. 2008, [18] W.J.J. Gao, et. al. 2010, [19] K. Xie, et. al. 2010, [20] W.J. Gao, et. al. 2011, [21] P. Weiland, et. al. 2010, [22] C.A. de Lemos Chernicharo, et. al. 2007, [23] A. Akram (c), et. al. 2008, [24] A.Y. Hu, et. al. 2006, [25] E. Kocadagistan, et. al. 2007, [26] T. Wang, et. al. 2009, [27] J. Ho, S et. al. 2010, [28] A. Pierkiel, et. al. 2005, [29] I.S. Chang, et. al. 1994.

Table 3.4 Concentrations of selected elements in different dairy wastewaters.

3.4 LITERATURE REVIEW

Research in the area of application of submerged anaerobic membrane bioreactors (SAnMBRs) in treating different types of wastewater is on its improving stage, thus mainly lab-scale experiments have been published. It is worth mentioning that published research regarding submerged conditions was limited, and mainly focused on membrane fouling and fouling control, as well as control of methane yield. Bacteria consortia stabilization was not thoroughly explained in the literature, thus the need for further research in order for this promising technology to be economically attractive for industrial stakeholders and better understood.

3.4.1 Energy recovery, biogas production and Removal efficiencies

The main point of applying anaerobic digestion is the biogas production. It has been applied to different wastewaters with large fractions of organics in it, obtaining biogas in continuous mode in an AnMBR configuration [P.M. Sutton, et. al. 2010]. The observed methane yield, CH_4, ranged from 0.23-0.33 l CH_4/grCOD_r [H. Lin (b), et. al. 2011, A. Saddoud (a), et. al.2007, A. Saddoud (b), et. al.2007, J. Ho, et. al. 2009, A.Y. Hu, et. al. 2006, D. Martinez-Sosa, et. al. 2011], which is a bit lower from the theoretical yield of 0.395 l CH_4/grCOD_r at 36°C. These values can be due to methane solubility [N. Brown, et. al. 2006], which is highly dependent on the operational temperature, and to some inhibitors associated with the anaerobic process [Y. Chen, et. al. 2008] such as organics, sulfide, ammonia, light and heavy metal ions. Solubility of methane is around 1.5 times higher at 15°C than at 35°C for a regular 70% methane content on the biogas. Therefore it is of high interest to release this methane from

wastewaters and capture it due to the fact that if lost dissolved with the effluent it can cause further greenhouse emissions posing a bigger challenge for energy recovery.

The biogas produced by AnMBRs is fairly composed by 55-90% methane, 3-15% CO_2 and 0-15% N [H. Lin (b), et. al. 2011, W.J.J. Gao, et. al. 2010, K. Xie, et. al. 2010, A. Saddoud (b), et. al.2007 J. Ho, et. al. 2009A.Y. Hu, et. al. 2006]. It has been reported that up to 98% of the influent COD in an AnMBR can be converted to biogas [P.J. Van Zyl, et. al. 2008], though it varies with the composition of the wastewater being treated. After the methane rich biogas has been captured it can have different applications like generation of electricity, heating the bioreactor, production of fuel, or even covering all the demand of energy needed to run the process [F. Meng, et. al. 2007] and still having more energy to use in the factory [P.J. Van Zyl, et. al. 2008]. During a case study 2.02 KWh/kg COD_r could be recycled from an AnMBR working with synthetic wastewater [P.J. Van Zyl, et. al. 2008], which was more than enough to make the whole system work. The methane production can be affected by many factors, some controllable and some not, such as high temperatures which are known to foster bacteria growth, thus the substrate utilization rates will be higher, with the final result of higher methane production. Nonetheless, some authors confirm that temperature fluctuations do not have any effect on biogas production in SAnMBRs [W.J. Gao, et. al. 2011]. On the other hand, the thermophilic range of temperature is very sensitive to changes and needs more time to adapt to the new conditions of temperature in case of shocks. Moreover, methanogenic bacteria work within a narrow pH range between 6.5 and 8.5, being severely affected if it falls out of the range, with the best conditions between 6.8 and 7.5 [P. Weiland, et. al. 2010]. The degraded

organic compounds composition also play a big role in methane production and composition percentages of the biogas produced [C.A. de Lemos Chernicharo, et. al. 2007]. High content of carbohydrates in organic wastes such as corn silage or biowaste can enhance the production of gas and the percentage of methane in it [C.A. de Lemos Chernicharo, et. al. 2007].

AnMBR operations aim to decrease the amount of organic carbon present in the wastewater before the effluent is discharged or recycled. In order to ensure the success of this objective, the research community has considered measuring the OC removal from the influent, taking samples from the effluent to compare and calculate the removal efficiency. Investigators have tested different wastewaters with concentrations of COD ranging from as low as 162 mg/L [Y. An, et. al. 2009] to 10,000 mg/L for kraft evaporator condensate [H.J. Lin, et. al.2009] or even 18,000 mg/L for a petrochemical effluent with high-strength composed by short-chain fatty acids [P.J. Van Zyl, et. al. 2008]. COD removal efficiencies vary from 76% [A. Saddoud, et. al. 2006] up to 99% [Z. Huang, et. al. 2008, H.J. Lin, et. al.2009]. The removal efficiency of BOD_5 has been reported to be as high as 99% [A. Saddoud (b), et. al. 2007, H.J. Lin, et. al.2009].

Removal efficiency of TSS has been reported to be higher than 99% [A. Saddoud (b), et. al. 2007, E. Kocadagistan, et. al. 2007]. Also, regarding pathogens, namely Escherichia coli and Enteroccoci, total removal could be attained. Therefore, in general the effluents have a quality enough to be used in unrestricted crop irrigation [A. Saddoud, et. al. 2006].

It has been proved that pH shock has a negative effect in COD removal efficiency causing severe long-lasting alterations [W.J.J. Gao, et. al. 2010]. A research was carried out to test pH shocks in the MLSS of a bioreactor and its effects, giving as a result severe alterations in the membrane filtration performance and biogas production. Three pH shocks were tested and the COD removal efficiency was accounted for the impact. At pH 8.0 the impact was low with a quick recovery of the system, but at pH shocks of 9.1 and 10.0 the system was severely affected jumping from a COD removal efficiency of nearly 90% to less than 75% and 30% for the shocks of 9.1 and 10.0, respectively.

Hongjun Lin (2011) operated a lab-scale SAnMBR for 106 days for secondary treatment using municipal wastewater. The results obtained were used to design a full scale SAnMBR. The COD removal efficiency was around 90% and a methane yield rate of 0.26 l CH_4/grCOD_r. Biogas was continuously collected with a composition of 75–85% CH_4, 5–8% CO_2 and 5–15% N_2. Neither nitrogen nor phosphorous removal was observed, but the effluent was beneficial for irrigation purposes.

A. Saddoud (a), et. al. 2007 has worked with a two-phase anaerobic bioreactor treating cheese whey wastewater. The system consisted of an acidogenic tank followed by a methanogenic reactor, with completely mixed liquor, and a membrane filtration module to allow the removal of SCOD while accomplishing total sludge retention. The HRT of the first tank was set at 1 day, achieving an acidification of 52.25% with a concentration of VFA up to 5 g/l with a composition of 24.7% propionic acid and the rest acetic acid. The second tank had a maximum OLR of 19.78 gr COD/l d, having a 4 days HRT and under these conditions have achieved removal efficiencies of BOD_5

and COD of 79% and 83%, respectively. In this two-phase anaerobic system the average removals of BOD_5, TSS and COD reached 99%, 100% and 98.5%, respectively. The methane content in the biogas was higher than 70% with a maximum yield of 0.3 l $CH_4/grCOD_r$.

Municipal wastewater was treated in a cross-flow ultrafiltration membrane system coupled to an anaerobic bioreactor operating at 37°C [A. Saddoud (b), et. al.2007]. Removal efficiencies of 100%, 88% and 90% were achieved for TSS, BOD and SCOD, respectively. Working with an OLR range from 0.23 to 2 gr COD/l d it could be possible to obtain SCOD values lower than 85 mg/l. Biogas production presented an increasing pattern with increasing OLRs up to a maximum average of 0.27 l $CH_4/grCOD_r$. After 140 days of operation the biogas composition had in average 70% of methane. The effluent was observed to have high quality in microbiological aspects and fulfilled the WHO guidelines for unrestricted irrigation.

D. Martinez-Sosa, et. al. 2011 worked with municipal wastewater operating during 100 days a pilot scale SAnMBR with a side stream filtration unit. The reactor was ran under mesophilic and afterward psychrophilic conditions within the critical flux conditions (7 L/m^2hr) at 35°C. The OLR varied from 0.6 to 1.1 gr COD/L d during long periods in mesophilic conditions. Loading rate variations could be explained by regular fluctuations in the influent COD concentrations. Under these mesophilic conditions the removal efficiency for COD reached close to 90%. When the temperature was reduced to psychrophilic conditions (20°C), a drop in the removal efficiency of COD was observed to go from 90% to 82%. The major VFA present in the bioreactor was acetic acid with concentrations fluctuating from 5-65 mgCOD/l and

100 mgCOD/l under mesophilic and physhrophilic conditions, respectively, showing a decreasing trend of acetate consumption by methanogenic bacteria at lower temperatures. However, the concentrations of acetic acid in the permeate were always under 1 mgCOD/l. Under mesophilic conditions methane yield was 0.27 l CH_4/grCOD_r with 80% of methane in the biogas. Under psychrophilic conditions methane yield was 0.23 l CH_4/grCOD_r with a composition of 88%.

3.4.2 Treated wastewaters

According to reported study cases in the literature, almost all authors have worked with bench-scale designs [A. Akram (d), et. al. 2008, A.Y. Hu, et. al. 2006, E. Kocadagistan, et. al. 2007, T. Wang, et. al. 2009, J. Ho, et. al. 2010] and no author has published a scientific article related to industrial-scale experiments. AnMBRs were applied for the rtreatment of different wastewater types like municipal wastewaters [Y. An, et. al. 2009] and raw domestic wastewaters [A.Y. Hu, et. al. 2006, E. Kocadagistan, et. al. 2007, A. Saddoud, et. al. 2006, S.H. Baek, et. al. 2006], white waters from paper mills and pulp [J.W.J. Gao, et. al. 2010, H. Lin (b), et. al. 2011] or even petrochemical effluents [P.J. Van Zyl, et. al. 2008] (Table 3.5 and Table 3.6).

It has been stated that AnMBR is quite sensitive to significant fluctuations in the composition of the influent and to toxic compounds present in wastewaters due to the fact that the microorganisms may not be able to adapt to the new conditions with the further instability of the system, not being able to reach steady state conditions [A. Saddoud, et. al. 2009]. As what it refers to toxicity, it is accounted in terms of toxic levels rather than toxic compounds, as any chemical in enough concentrations is toxic.

Nevertheless, this situation can be controlled and minimized taking design measures like extending the SRT [C.A. de Lemos Chernicharo, et. al. 2007], which is the case for AnMBRs, or even removing the toxic chemicals before they enter the anaerobic bioreactor [C.A. de Lemos Chernicharo, et. al. 2007, B.Q. Liao, et. al. 2010], leading to safe operational conditions for AnMBRs.

AnMBRs have demonstrated to be capable of operating at high MLSS concentrations, like when working with swine manure at 49 g/l [J. Zhang, et. al. 2007] or municipal waste of 50 g/l [M. Xu, et. al. 2011].

Type of wastewater	Working Volume (L)	MLSS (g/L)	OLR (Kg_{COD}/m^3d)	HRT (h)	SRT (d)	Temp. (°C)	Influent COD (mg/L)	Effluent COD (mg/L)	Max. COD removal (%)
Sucrose-based	3	11,45-16,12 (VSS)	6-16	6-40	≈250	34-36	4000	31-484	98
Sucrose-based	3	1,68-9,69 (VSS)	4-4,8	15-80	≈150	34-36	4000	160-240	96
Meat extract/Peptone -based	3	2,5-3,9 (VSS)	[b]	6	150	34-36	430-470	7-29 (SCOD)	96
Synthetic sewage	10	-	≈5	24	50	30	500	20	>96
Synthetic simulating municipal	4	6-14	1	12	-	14-26	500	≈40 to ≈200	95
Synthetic simulating municipal	5	5-11,24	1,1-1,65	8-12	30-Infinite	25-30	550	-	97
Glucose-based	3	3,5-5,5	-	3-48	-	35	150-920	21,76-50,38	95
Synthetic simulating municipal	3	4,3-5,02	-	3-24	-	35	460	27,1-47,9	95
Low-strength	5 (Total)	4,3-5,72	1,1	12	30-60	25-30	550	5	99
Volatile fatty acid mixtures	3,7	37-43	-	-	-	30-55	-	-	-
Volatile fatty acid mixtures	3,7	35-40	10-70	-	-	30	5000-10000	-	-
Volatile fatty acid mixtures	3,7	35-40	14885	-	-	55	5000-10000	-	-
Volatile fatty acid mixtures	3,8	13-35	<15	-	-	30-55	10000	-	-
Volatile fatty acid mixtures	2	41 (Final)	10-15	-	-	55	10000-17000	-	
Synthetic simulating alcohol distillery wastewater	4,5	1,3-1,9	4	6,5 d	-	54-56	4200-5800		>84
Sodium acetate/Sodium propionate-based	2	-	4,1-6,2	1,8-3	-	35	513	3-11	99
Synthetic containing formic acid	10,9	1,03-1,81	-	8	-	31-35	-	-	-
Synthetic simulating municipal	50	≈0,5 to ≈4	1	-	-	37	800-1200	-	-
Whey/Sucrose-based	11	5,5-20,4	1,5-13	-	30-40	34-36	-	-	-

Type of wastewater	Working Volume (L)	MLSS (g/L)	OLR (Kg_{COD}/m^3d)	HRT (h)	SRT (d)	Temp. (°C)	Influent COD (mg/L)	Effluent COD (mg/L)	Max. COD removal (%)
Synthetic of COD of 800 mg/L	25 (Total)	4-10	0,46-5,76	10,4	Infinite	-	800-2500	-	85
Synthetic sewage	3	-	2	20	250	34-36	445-485		98,8 (DOC)
Synthetic with nitrates	4,8	2,23	-	2 d	35	-	87-191	-	-
Molasse-based	9	1,6-10 (VSS)	5-12,2	-	-	27-33	700-24200	81	-

[b] Value not reported

Table 3.5 Summary of AnMBR performance for synthetic wastewaters. Adapted from G. Skouteris et. al. 2012.

Type of wastewater	Working Volume (L)	MLSS (g/L)	OLR ($KgCOD/m^3d$)	HRT (h)	SRT (d)	Temp. (°C)	Influent COD (mg/L)	Effluent COD (mg/L)	Max. COD removal (%)
Landfill leachate	29 (Total)	[b]	0,7-4,9	24-168	-	35	5000	417	95
Thermo-chemical whitewater	10 (Total)	4,9-10,7	2,0-2,8	-	≈280	36-38	2782-3350	300	90
Thermo-chemical whitewater	10	8,3-9	1,66-1,94	-	-	36-38	1823-3504	217,5-421,1	87
Kraft evaporator condensate	10 (Total)	3,5-8,5	1-7	-	200-260	37-56	2400-2600	50-200	95
Kraft evaporator condensate	10 (Total)	-	2,3-13,3	-	-	36-56	9500-10500	74-276	99
Kraft evaporator condensate	10	3,7-5,7	-	-	-	36-38	5500-10000	63-192	-
Thermo-chemical whitewater	10	6,7-11,3	2,6-4,8	-	280	36-38	2782-3460	280-425	90
Swine manure	6	-	1-3 (Kg_{VSS}/m^3d)	-	-	36-38	-	200-250	>96
Cheese whey-based	20	-	3-19,78	1-4 d	-	35-39	-	-	≈98,5
Slaughter house wastewater	50	10,1	1,59-16,32	30-80	-	37	15880	-	>99
Brewery wastewater	4,5	12-25 (VSS)	12	-	-	30	2300	190	99
Landfill leachate	3	7,2-10,8 (VSS)	8-11,8	1,1-19 d	30-300	10-35	-	-	>95 (S COD)
Fischer Tropsch acid water	23	30	25 (max)	31,5	175	37	19101	612	-
Dairy manure-based	200	-	2,4 (Kg_{VSS}/m^3d)	9 d	28	-	-	-	92
Kraft evaporator condensate	3,5	2,1-24	1-24	-	-	36-38	5600-10000	50-200	99
Landfill leachate	50	<3 (VSS)	1-6,27	7 d	-	37	15000-41000	960-4100	>92
Swine manure	5	-	1-2 (Kg_{VSS}/m^3d)	6	118-211	-	-	-	>95

[b] Value not reported

Table 3.6 Summary of AnMBR performance for wastewaters other than municipal and synthetic. Adapted from G. Skouteris et. al. 2012.

3.4.3 Operational conditions

It has been reported a wide variety of operating conditions combined together applied to AnMBR process, such as the hydrodynamic conditions namely temperature, sludge and hydraulic retention times, and pH. A very common way to reduce fouling in the surface of the membrane in a side-stream AnMBR configuration, is by the implementation of high cross-flow velocities in the order of 2-3 m/s. Nevertheless, it has been studied that at higher shear conditions the microorganisms are negatively affected [K.-H. Choo, et. al. 1996]. On the other hand, this shear condition can be attained by sparging biogas under the membrane in a SAnMBR configuration [H.J. Lin, et. al. 2009, Z. Huang, et. al. 2008, A.Y. Hu, et. al. 2006, A. Akram (d), et. al. 2008, D. Jeison, et. al. 2007]. However, till now there has not been a thorough study of the biogas sparging rate effects on the bioreactor efficiency or the bacteria community in an AnMBR.

HRT values range from a few hours (2 hr) [J. Kim, et. al. 2011] to a few days (20 d) [E. Jeong, et. al. 2010], whereas SRT values range from 18 d [S.H. Baek, et. al. 2006] or 30 d [Z. Huang, et. al. 2008], to about a year [A.P. Trzcinski, et. al. 2009] or even more, which indicates there was practically no sludge excess produced in the experiment [Z. Huang, et. al. 2011]. In general at higher HRT values the substrate removal efficiency is improved but to a limited extent. Most of the literature reviewed, showed that authors worked with SRT of more than 150 days, and still is the major parameter responsible for membrane fouling and the reactor performance. It was found that the longer the SRT the higher the SCOD removal [A.P. Trzcinski (a), et. al. 2010], in contrast with another experiment conducted by S.H. Baek, et. al. 2010 where SRT

was decreased from 213 to 40 days and no negative effects were observed on the membrane fouling or treatment efficiency. SRT values and its relation with the treatment efficiency or fouling are deeply connected with the HRT applied and the influent composition. In general, at high HRT and SRT operating values in an AnMBR, the system efficiency can be enhanced as well as methane production and resulting in a reduction of the sludge produced [J. Ho, et. al. 2009].

As stated hereinbefore, the pH in anaerobic systems is close to neutral values of 6.5-8.5, an optimal range of 6.8-7.5 [P. Weiland, et. al. 2010]. This narrow range is usually reached with the use of alkalinity to achieve neutralization, though the need of alkalinity is high. However this seems to be to best solution.

Depending on the temperature that an anaerobic system is working, it can be classified in psychrophilic (0-20°C), mesophilic (20-42°C) or thermophilic (45-75°C) [K.V. Rajeshwari, et. al. 2000]. Most of the AnMBRs in the literature were operated either in the mesophilic range [D. Martinez-Sosa, et. al. 2011, A.P. Trzcinski (a), et. al. 2010, H.J. Lin, et. al.2009, D. Jeison (b), et. al. 2008] or the thermophilic range [H.J. Lin, et. al.2009, J. Kim, et. al. 2007, D. Jeison, et. al. 2007], even though psychrophilic temperatures were also tested [D. Martinez-Sosa, et. al. 2011, A.P. Trzcinski (a), et. al. 2010, A.P. Trzcinski (b), et. al. 2010]. The temperature of the bioreactor influences the COD removal efficiency [A. Santos, et. al. 2011] and improves methanogenesis, yielding better results with increasing temperature. Moreover, some authors state that working at thermophilic temperatures the AnMBR could operate with higher OLRs than if operated at mesophilic temperatures. Values greater than 14 gr COD/l d were achieved in an AnMBR at thermophilic temperature, whereas at mesophilic range it

was not able to even reach values greater than 10 gr COD/l d [D. Jeison (b), et. al. 2008]. Generally speaking, at higher ORLs the COD removal efficiency is negatively affected because it reduces microbial activity, and VFAs may accumulate deteriorating the system's performance [K. Wong, et. al. 2009, J. Bohdziewicz, et. al. 2008, K.C. Wijekoon, et. al. 2011].

3.4.4 Membrane fouling issues

Up to now membrane fouling could not be properly arrested and is still the limiting obstacle for industrial application of AnMBRs in wastewater treatment. This phenomenon can pose a threat to the system performance, causing higher cleaning frequency which affects the membrane lifespan increasing costs to replace them and increasing the energy required for recirculation of the sludge or gas sparging. Membrane fouling is highly dependent on the membrane material and the characteristics of the sludge treated. Generally, membranes that can be applied to aerobic digestion can also be used in anaerobic processes though the MLSS in the latter is substantially different from that of the aerobic system, thus presenting particular characteristics on the membrane fouling. Studies have developed several techniques to classify membrane fouling [F. Meng, et. al. 2010], helping to better understand fouling in AnMBRs.

Three 6-L SAnMBRs were investigated to treat synthetic low-strength wastewater, working with three SRT (30 days, 60 days and infinite days), resulting in HRT of 8hr, 10hr and 12hr [Z. Huang, et. al. 2011]. During all the operation conditions COD removal efficiency achieved values higher than 97%. At infinite SRT the maximum biogas yield was 0.056 l CH_4/grMLVSS day. Biogas production increased with lower

HRT and higher SRT because of higher OLR or dominancy of methane producing bacteria. Decreasing HRT improved bacterial growth and increased the soluble microbial products (SMP), but increased fouling. Lower carbohydrate to protein ratio had a negative effect on fouling. At HRT of 12hr, there was no observed effect of SRT on the MLSS concentration and fouling could be controlled because of varying SMP characteristics, i.e. high membrane fouling rate at higher carbohydrate to protein ratio in the SMP. At HRTs of 8hr and 10hr and infinite SRT, maximum values of MLSS and SMP were achieved, increasing sedimentation and cake layer formation. At higher SRTs, extracellular polymeric compounds were not enough to reduce particles flocculation and their size, aggravating membrane fouling.

Though a firm definition of membrane fouling cannot be given, there is a common classification between reversible and irreversible fouling, depending on the cleaning procedures followed. Reversible fouling can be sub-classified in removable or irremovable fouling. According to this, if the fouling can be removed by physical actions like back flush or relaxation of the membrane in a cross-flow configuration, it is said to be removable, but if it requires chemical cleaning it is called irremovable. On the other hand, irreversible fouling cannot be suppressed by any means of cleaning, thus is permanent.

3.4.4.1 Parameters influencing membrane fouling

Depending on the membrane setup, in AnMBRs permeate fluxes in systems working with municipal wastewaters in side-stream configuration are significantly affected by cross-flow speed and TMP values, whereas in submerged conditions the flux is affected by the pressure on the membranes, gas sparging rates and membrane

relaxation time [P.R. Bérubé, et. al. 2006]. Despite that, gas sparging was found to enhance permeate fluxes when applied to tubular membranes in side stream configuration. Therefore, the application of a two-phase flow (gas and liquid) in a tubular membrane could pose a solution for fouling control in such cases [A. Torres, et. al. 2011].

Shear forces applied to the biomass in an AnMBR with a side-stream configuration are commonly higher than that applied in submerged conditions, thus their performance will vary greatly. These forces represent a great importance in membrane fouling issues due to the fact that higher magnitudes of shear forces have a detrimental effect over microorganisms' activity and biofloc sizes, thus releasing more SMP into the liquid [H.J. Lin, et. al.2009, D. Jeison, et. al. 2009], and further fouling the membranes. On the other hand, particles can be kept away from the membrane surface when working with high shear stress, as it is the case of gas sparging, reducing fouling [K. Calderón, et. al. 2011, P.R. Bérubé, et. al. 2006]. Toxic shocks have been reported to have negative effects in membrane efficiency, deflocculating sludge [B.Q. Liao, et. al. 2010]. Materials used in membranes have also an effect in fouling [P.R. Bérubé, et. al. 2006, D.W. Gao, et. al. 2010].

It is worth to mention that membrane fouling is strongly linked to the pore size of the membrane. The selection of the membrane pore size will depend then on the MLSS being filtered. The larger the membrane pore sizes, the higher initial permeate fluxes and fouling rates. This fouling is believed to be caused by internal pore fouling, because cake layer is formed independently from pore sizes [P.R. Bérubé, et. al. 2006].

3.4.4.2 Membrane fouling mitigation techniques

The main goal of investigating membrane fouling mitigation is for developing control measures and cleaning procedures. Five different techniques can be applied to AnMBR systems to reduce or control fouling, which will depend on the parameters controlling the fouling: (1) pretreating the influent, (2) optimizing operation conditions, (3) modification of the activated sludge, (4) optimization of membrane module, and (5) cleaning the membrane.

3.4.4.2.1 Pretreating the influent

Influent composition may pose severe impacts over membrane fouling. Extreme values of pH found in some wastewaters affects both the microbial community performance and membrane efficiency and lifespan. It has been found that one characteristic of cake layer formation is its rich composition in iron, magnesium, aluminum, calcium and silice [H. Lin (b), et. al. 2011]. Wastewater pretreatment techniques aim to remove any excess of these materials by filtration [J. Grundestam, et. al. 2007], pH adjustment [A. Saddoud (a), et. al.2007], or the establishment of local wastewater limits.

3.4.4.2.2 Optimizing operation conditions

Hydrodynamic conditions, permeate flux and retention times are the principal operational parameters, as well as temperature, pH and MLSS concentration. To have a better control of membrane fouling, gas sparging intensity and time could be increased in submerged conditions, or the cross-flow velocity in side-stream configurations could be higher. Nevertheless, this could cause defloculation, increasing the number of small-sized particles and resulting in higher concentration of SMP, greatly increasing membrane fouling [H.J. Lin, et. al. 2009, D. Jeison, et. al.

2009]. Working at sustainable flux is a commonly used technique to control membrane fouling.

3.4.4.2.3 Modification of the activated sludge

MLSS characteristics of an AnMBR can be modified by adding coagulants, carriers, adsorbent agents or other chemicals, with the purpose of reducing membrane fouling. These additives can be used separately or combined together in an appropriate way, producing coagulation, adsorption of SMP in excess, increasing bioflocs size, among others [A. Drews, et. al. 2010].

PAC is widespread used for enhancing flux in MBRs. Thus, it has been reported to reduce cake layer formation and fouling in a continuous way [H. Park, et. al. 1999]. Several studies have confirmed that adding PAC in AnMBRs has improved membrane performance [H. Park, et. al. 1999, I. Vyrides, et. al. 2009, K.-H. Choo, et. al. 2000, A. Akram (c), et. al. 2008]. Nonetheless, PAC in excess could pose a threat to membrane fouling as it acts as the foulant [A. Akram (d), et. al. 2008, Z. Ying, et. al. 2006]. Vermiculite, bentonite and zeolite have been found to have a positive impact over membrane fouling control in AnMBRs [S. Malamis, et. al. 2009, A. Damayanti, et. al. 2011]. These additives are able to tackle down ammonium and soluble organics from the supernatant due to their ion exchange capacity and high adsorption rate, enhancing the effluent quality and performance of the system.

Recently, an experiment was conducted investigating the possible use of fullerene C_{60} nanoparticle to control membrane fouling, giving promising results by significantly avoiding bacteria to attach to the membrane surface. Other prospective additives for

fouling control include copper and titanium oxide or magnesium-based nanoparticles [S.-R. Chae, et. al. 2009], posing a novel technology for AnMBRs.

3.4.4.2.4 Optimization of membrane module

A widely used technique to prevent and control fouling is the modification of the membrane surface to enhance its hydrophilic characteristics since the main part that can be improved is its surface. Modifying the surface of the membrane can be attained by surface blending, coating or grafting, plasma treatment, etc. with the objective of attaching polar organic groups. Many plasmas have been used in investigations, like water, oxygen, nitrogen, carbon dioxide and ammonia [H.-Y. Yu (a), et. al. 2005, H.-Y. Yu (b), et. al. 2005, H.-Y. Yu (a), et. al. 2008, H.-Y. Yu (b), et. al. 2008, H.Y. Yu, et. al. 2007]. The main characteristic of plasma modification is that the properties of the surface and compatibility with microorganisms can be improved separately without affecting the main characteristics of the rest of the materials.

J. Kochan, et. al. 2009, have filtered sludge supernatant with coated UF flat-sheet membranes, using different coatings (branched poly-allylamine chloride and other two similar compounds), yielding positive results by lowering fouling rates. The main disadvantage of applying this technique is the low physical tolerance of the membrane and the coating chemical stability when working in the conditions of the bioreactor. However, to counteract this problem the regular PVDF membranes in the UF range can be coated with an amphiphilic graft copolymer giving origin to the thin film composite nano-filtration membranes (TFC NF) [A. Asatekin, et. al. 2006]. This membrane showed high resistance to irremovable fouling during a 10-day filtration using concentrations higher than 1000 mg/l of some organic foulants.

3.4.4.2.5 Cleaning the membrane

Despite all the fouling control measures that can be applied, fouling cannot be 100% avoided but physical, biological and chemical cleaning could regenerate the membrane to a great extent. The most common physical technique used in MBRs is back flushing and membrane relaxation or even the recent study of making use of the water hammer utilizing an automatic valve in the effluent side [F. Broens, et. al. 2012]. Ultrasound can be applied as well on the membrane surface to control cake formation [X. Wen, et. al. 2008]. However, it could cause membrane damage and affect biological activity.

The second technique mostly used is chemicals in cases where fouling has not been reduced to the required levels. Several chemicals have been investigated to be used in AnMBR systems, like NaOH, NaClO, HCl or EDTA, as well as other acids like nitric and citric in low concentrations [H. Lin (a), et. al.2011, J. Zhang, et. al. 2007, D. Jeison, et. al.2007, B. Mahendran, et. al. 2011]. It has been proved that when combining pairs of chemicals rather than applying one at a time, the cleaning results are more promising [T. Mohammadi, et. al. 2003].

3.4.5 Inhibitors

The inhibition concentrations or toxicity levels reported for substances found in an anaerobic digestion showed a wide variation. The major reason is that anaerobic digestion is a very complex process where mechanisms like pH, acclimation, temperature and other factors can highly influence the inhibition phenomenon, fostering or preventing it. Inhibition concentrations for different substances were adapted from Y. Chen, et. al. 2008, and are shown in Table 3.7. The values shown

represent the minimum concentration over which an adverse effect over methanogen bacteria was found within several studies over the literature.

Substance	Inhibition Concentration [mg/l]
Free Ammonia (NH_3)	200-1700
H_2S	50-125
Al	1000
Ca	120-300
Mg	400
K	400
Na	3500-5500

Table 3.7 Maximum concentration of inhibiting substances in anaerobic process

CHAPTER 4

RESEARCH OBJECTIVES

4.1 OBJECTIVES

Previously it was stated the current status and future guidelines to follow within the field of application of anaerobic membrane bioreactors in wastewater treatment, as well as some points were made for submerged conditions. Though the application of SAnMBRs is on its early stages it has promising results and hence the need to improve fouling control measures and bacteria consortia stabilization, as well as a better study of its biokinetics.

The costs of the membranes are high, being the main reason to offset stakeholders from its application. The promising results obtained in lab-scale experiments with different setups, hydraulic configurations and operating modes is well availed by the whole literature, though drastically improvement is needed to further develop this kind of technology.

It has been stated that high biomass concentration in the SAnMBRs improve the permeate quality mainly because SRT is infinite (biomass loss is close to zero, except for sludge samples taken for analysis). In contrast, this may cause serious membrane fouling if not properly controlled on time, reducing the bioreactors COD removal and

biogas production efficiencies, offsetting any possible beneficial application of it. Therefore the need for investigation to find an optimum membrane efficiency stable with time, applying different OLR and SRT, as well as controlling membrane fouling to the minimal without chemical cleaning application.

Based on all these points, the objectives of the thesis were as follow:

General Objective

4.1. Investigate the use of SAnMBR treating synthetic dairy wastewater (SDW)

Specific Objectives

4.2. Investigate the effect of MLSS on the efficiency

4.3. Investigate the effect of OLR on the efficiency

4.4. Quantify and characterize the biogas production

4.5. Investigate the biokinetic coefficients of SAnMBR

It is believed that this investigation can lead to further understanding of submerged conditions used in anaerobic membrane bioreactors for wastewater treatment, and more in particular in the treatment of dairy wastewater. Furthermore, it provides valuable information regarding operating conditions to be used for the design of a pilot scale treatment plant.

CHAPTER 5

EQUIPMENT AND METHODOLOGY

DESCRIPTION

5.1 EXPERIMENT BUILD UP AND GENERAL DESCRIPTION

The research is meant to be developed in a 90-days continuous filtration and data gathering period. The period was divided into four stages, namely bacteria acclimatization and stabilization, and the experiment at three different MLSS concentrations with a varying OLR in each. Experiment setup took place in the Environmental Engineering Laboratories of the Civil Engineering Department, with the cooperation of the Research Institute, at King Fahd University of Petroleum & Minerals.

The design of the lab-scale setup, as shown in Figure 5.1, Figure 5.2 and Figure 5.3, was built at the Mechanical Engineering Workshop of KFUPM, in Building 26.

Before starting the research, bacteria consortia was acclimatized to a synthetic dairy wastewater that resembles the real wastewater according to the average chemical parameters obtained in dairy factories. A short one-batch experiment was ran with these bacteria consortia in order to assess biogas production and pH stabilization

controlling measures. This experiment took place in Environmental Engineering lab with the analyses being conducted at the Research Institute. After acclimatization has been reached, the research started as soon as other materials were made available to run the whole experiment, like the bioreactor tank, peristaltic pump. Hereinafter, data was collected, analyzed and written down for final analyses.

The final report has the objective to tackle down I. the treatment efficiency obtained and biogas produced, and II. Biokinetics of a submerged AnMBR.

5.1.1 Making synthetic dairy wastewater

In order to reproduce the synthetic wastewater from the dairy industry, a thorough literature research was conducted as part of the Independent Research course. These results were then taken for the preparation of synthetic dairy wastewater following the literature as explained further ahead. Results of COD, BOD_5, pH, TP, PO_4-P, TKN, NH_4-N, Na^+, K^+, Ca^+, Mg^+, TS, TSS and TDS were taken into account when preparing and comparing the synthetized dairy wastewater.

Almarai whole milk was analyzed for COD at the Research Institute of KFUPM, with an average result of 176,000 ppm. As seen before in previous chapters, the average COD content in dairy wastewater could be said to be around 2000-6000 ppm, thus the need of dilution to achieve these figures. On the other hand Haley full cream powder milk contributed to a total of 3000 ppm COD every 2 gr.

5.1.2 Permeate quality

In order to guarantee the treatment efficiency, permeate and influent water quality has to be compared. Thus, COD removal efficiency is of high interest and is one of the

parameters used in wastewater treatment to verify the efficiency of the system. For this purpose COD was analyzed from the influent and permeate. Furthermore, bioreactor pH has to be measured and stabilized in case it is away from the neutral range, which is 6.5 –8.5.

5.1.3 Membrane performance

The continuous reactor was placed inside the hood of the laboratory at room temperature, i.e. mesophilic temperature range (≈25°C) during the whole experiment. Three different concentrations of MLSS and OLR combinations were tested, starting with the lowest amounts and increasing as following, respectively:

1. 5 g/l MLSS – 2000, 4000, 6000 and 8000 ppm COD,
2. 10 g/l MLSS – 2000, 4000, 6000 and 8000 ppm COD,
3. 15 g/l MLSS – 2000, 4000, 6000 and 8000 ppm COD.

Flux remained constant during the whole experiment, and to control membrane fouling, backwashing with distilled deionized water twice daily was the best choice with good results. The flux was set between 2 to 2.7 l/m^2h and kept as constant as it was possible.

The HRT was set at 70 d for the first 28 days (because bacteria were being stabilized, thus there was no permeate suction but only 50ml samples which account for the 70 d of HRT and SRT as well), then it was shifted to 10-11 days to test its behavior and was kept constant during the rest of the experiment.

5.1.4 Biogas production

Water displacement method was used to quantify the biogas obtained from the bioreactor. For the case, a graduated beaker was used to account for the volume of gas collected. This volume was then corrected for bioreactor temperature, compared with the theoretical yield at that temperature and finally expressed as l/grCOD_r.

5.1.5 Experimental design

To sum up the experimental design, in Table 5.1 a chronogram is shown typifying each modified parameter, the length of each stage with the settled parameters and the total length of the entire experiment.

The analysis of real dairy wastewater in order to prepare the synthetic one took place by the thorough analysis and research of literature published regarding dairy wastewater characteristics in different countries and for varying type of dairy industries (different end-products), as said in point 5.1.1. Real waste analysis could not take place due to the lack of access to it from any company in the Eastern Region of Saudi Arabia. It is worth mentioning that it was tried with effort to get at least one sample or the appropriate analyses from the factories, but with no success at all.

After the research in the literature the SDW was prepared and analyzed first to check its characteristics and how it fitted the average values for dairy wastewaters from different factories around the globe.

Day / Parmtr.	1-57	1-6	7-11	12-16	17-22	30-35	36-40	41-45	46-50	51-55	56-60	61-66	67-72
Stages	**Stabilization Stage**	**Stage I**				**Stage II**				**Stage III**			
MLSS [mg/l]	5000	5000				10000				15000			
COD [ppm]	2000	4000	6000	8000		2000	4000	6000	8000	2000	4000	6000	8000
Flux [l/m^{2}h]	0	2.07-2.3											
HRT [d]	70	10-11											

Table 5.1 Chronology of thesis work and development

5.2 MEMBRANE CHARACTERISTICS

The membranes that were used for this investigation are 4-packed tubular UF membranes of hydrophilic polyvinylidene fluoride (PVDF) with cross-flow from out to inside. It is characterized for its high chemical resistance and mechanical stability under pressure, and its stable filtration flux and excellent antifouling characteristics. They can be used for wastewater treatment, membrane bioreactors, clarification and concentration of fruit juices and oil-water separation. Technical specifications are detailed in Table 5.2.

5.3 CONTINUOUS BIOREACTOR CONFIGURATION

Figure 5.1, Figure 5.2 and Figure 5.3 sketch and show the continuous flow bioreactor setup used for the present study with its different equipment and instruments.

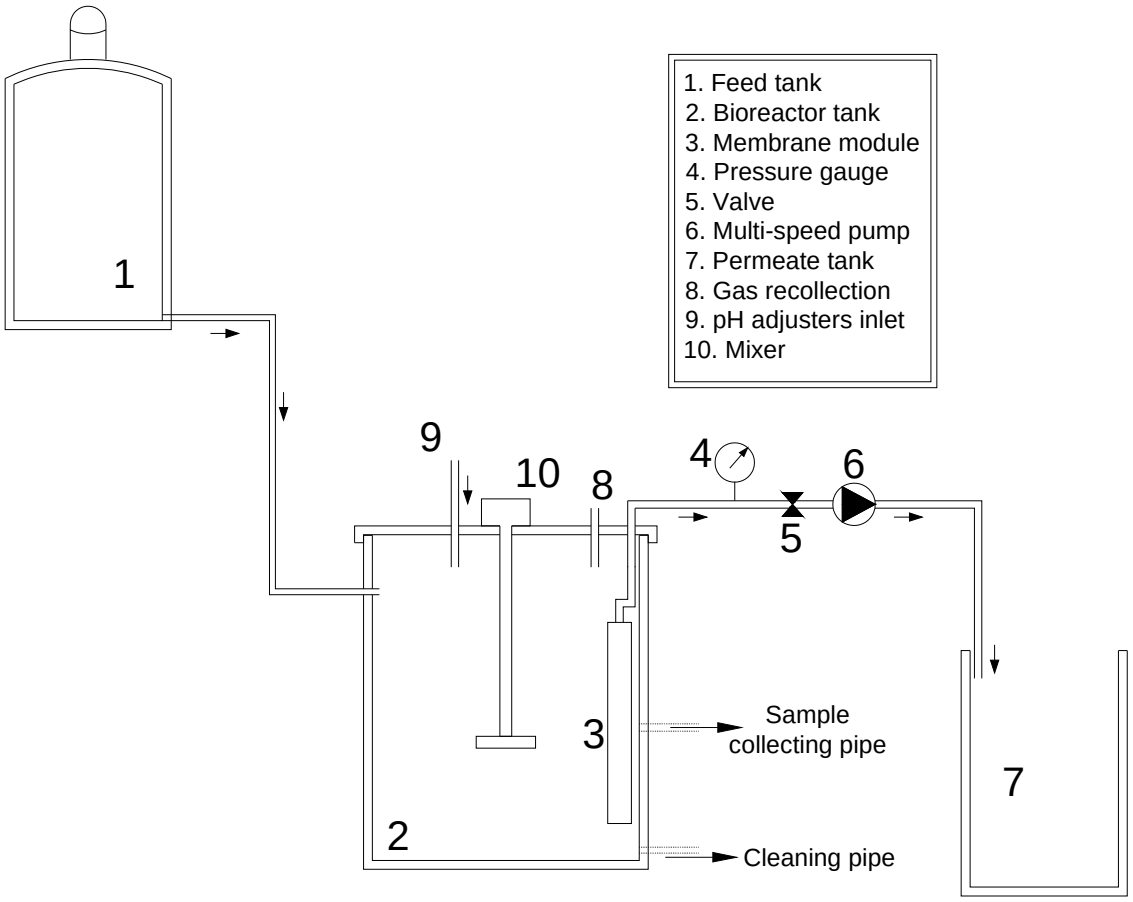

Figure 5.1 Bioreactor lab-scale sketch configuration

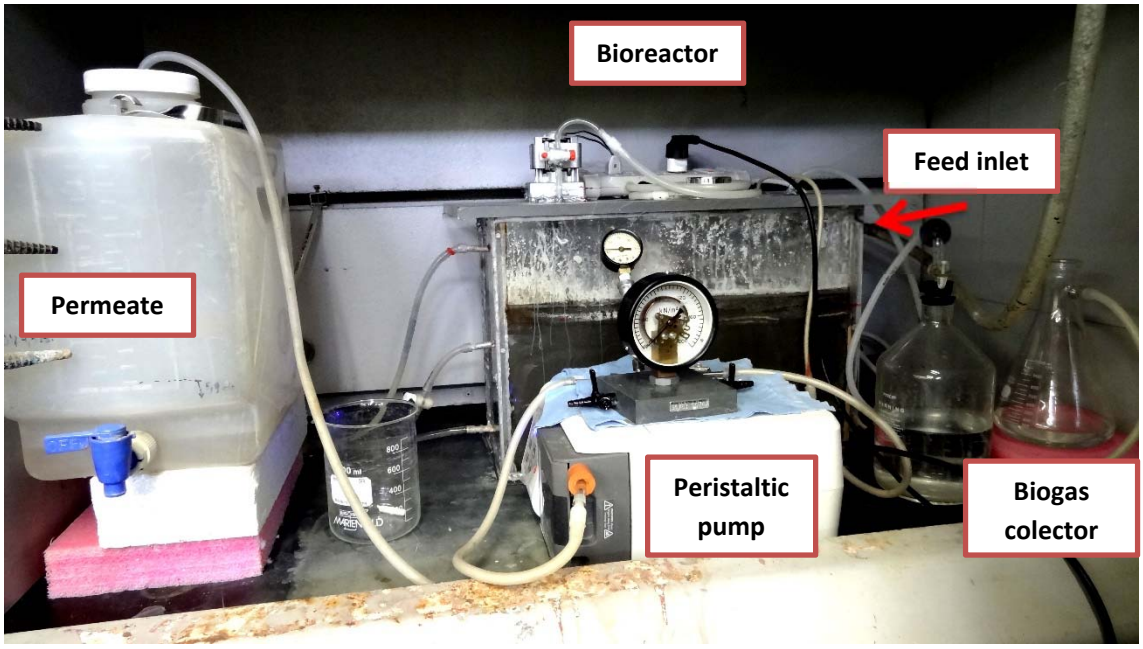

Figure 5.2 Bioreactor lab-scale setup

Figure 5.3 Full lab-scale Bioreactor setup

Parameter	Units	VFU-250a	Remarks
Water flux	l/m2h100kPa	> 500	At 25 °C and 100 kPa
Molecular weight cut off	Da	250,000	Dextrane mixture
Temperature range	°C	1-70	At pH=7 and 100 kPa
Pore size	µm	0.03-0.05	
pH range		2-10	At 25°C
Diameter "outer side"	mm	9.2	
Length	mm	340	Only tubes
Total length	mm	400	
Total Membrane area	m^2	0.04	
Permeate outlet with hose nozzle	mm	9	
Filtration direction		from outside to inside	submerged
Type		UF tubular	

Table 5.2 Membrane characteristics

5.4 SAMPLING FREQUENCY AND EQUIPMENT UTILIZED

For the development of the thesis project several equipment were utilized and analyses were performed following the Standard Methods 2005. All the analyses procedures that were followed can be found in the Standard Methods 2005 (Table 5.3).

It is worth mentioning that quality control of chemicals and equipment was always ran when possible. Thus, the pH meter was recalibrated at the beginning of the experiment with check points every day with standard solutions to control its stability. Turbidimeter Hach 2100AN is automatically calibrated, though controls with standards were ran every day before a reading was taken.

Regarding COD analysis a control with potassium hydrogen phthalate was performed with 3 different concentrations which are 50, 100 and 200 ppm of COD. This control took place 3 times in total: one at the beginning and two when reagents were changed.

Phosphate analyses were performed with a calibration every time they were done, thus this represents a control measure. Nonetheless, values read on the spectrophotometer were compared daily with previous values of calibration, and they were all accurate.

Parameter	Method	Equipment	Frequency
pH	Potentiometric – SM-4500H+B	JENWAY 924005 pH meter	Daily
Turbidity	Nephelometric – SM-2130B	HACH 2100AN Turbidimeter	Daily
COD	Closed reflux – SM-5220C	HACH COD reactor	Daily
Phosphate	Vanadomolybdophosphoric acid colorimetric method - SM-4500PC	JENWAY 6300 spectrophotometer	Daily
TSS	Gravimetric – SM-2540D	-	Twice a day
Biogas yield	Water displacement		Daily
CH4 Content	EPA - 8015	Agilent Technologies GC – 6890N	N/A

Table 5.3 Methods of different analyses performed.

5.5 MEMBRANE CLEANING

A minor inconvenient regarding membrane cleaning with an automated valve was presented, due to the lack of technical support. When the automated valve arrived (it was ordered from Germany), there was the need of technical expertise and a specialist was needed for the setup of it. Therefore this technique was abandoned and, as low flux was maintained during the filtration process (around 2.3 l/m^2 h), backwashing with distilled deionized water was sufficient to provide a full recovery of the filtration unit, i.e., the vacuum pressure and the flux (Figure 5.4).

Backwashing was performed twice daily, every 12 h, in order to obtain a constant flux. Time of backwashing varied from 10-30 minutes, depending on the fouling and the OLR at the time. This scheme was chosen after trying with different cleaning frequencies, starting from 45', 1h, 2h and 4h, with no improvement for the latter, but recoil of membrane performance was observed for the other three frequencies. Thus, when the cleaning frequency was less than 4 hr a noticeable increase in the permeate turbidity was observed. Therefore, as a frequency of less than 4 hr proved not to be a good choice and, due to the fact that up to a frequency of 4 hr no membrane performance improvement could be observed, a frequency of 12h was chosen. As a very low cleaning frequency was determined to be effective for the system's stability, cleaning once a day was also tested but the results were unsuccessful and have complicated the cleaning procedure with longer backwashing times. It shall be reminded that the less number of times the bacteria are bothered the better their performance, and a membrane cleaning represents a hassle for bacteria due to the change in the environment and steady state conditions of the flux and the system itself.

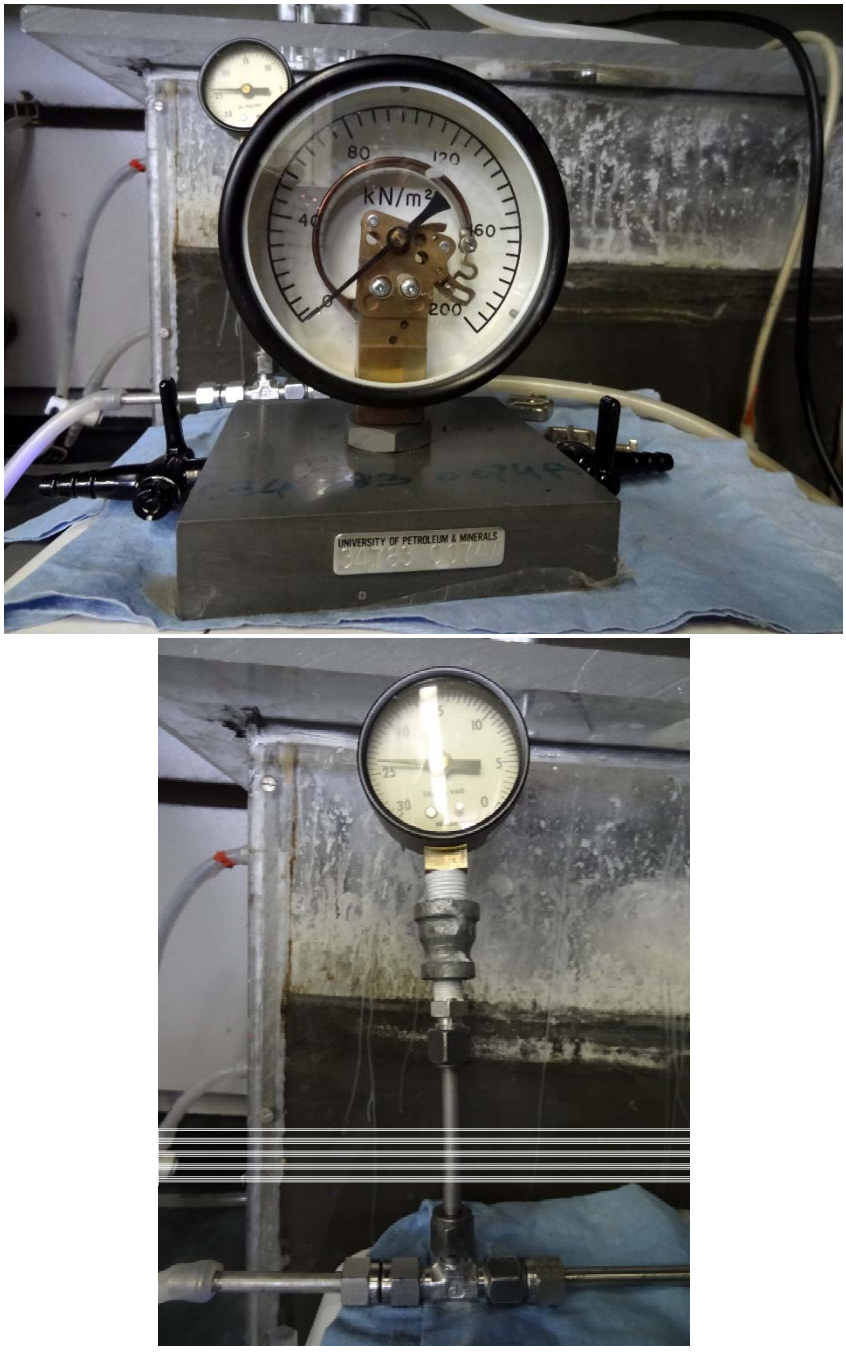

Figure 5.4 Pressure gauges used for (from top to bottom) measuring backwashing pressure and vacuum pressure in membrane.

CHAPTER 6

PRELIMINARY STUDIES

6.1 SYNTHETIZING DAIRY WASTEWATER

After a thorough review of the literature in the following table a summary of the main parameters with average values, or values most encountered within the literature, are shown in order to have an overall idea of the ranges within the ones synthetized dairy wastewater has to be.

The compositions of the powder milk and fresh liquid milk used to synthetize the dairy wastewater are described in Table 6.1. Compositions of each different source are compared to get a quick idea of the contribution of each one to the concentration of every component. Mainly the characteristics of each one are similar, only variations within 5% are observed, which is not considered a big difference. For storage and ease to handle purposes powder milk was chosen and freshly prepared when needed for the different analyses.

As it can be inferred from Table 6.2, milk itself does not provide with the sufficient nutrients for bacteria to grow, which is nitrogen, phosphorous, and metal traces like sodium, potassium and magnesium. The only metal trace found readily to be used is calcium but in very low amount. Calcium concentration has to be around 120 mg/ltr,

with an optimum value of less than 200 mg/ltr in order not to reach the inhibitory levels.

Several analyses were conducted over raw milk and fresh milk prepared with powder milk in order to compare their results and come up with a choice. A quick check of COD was made to both type of milks and it was found that fresh full fat milk (Almarai) contributed to 176,000 mg/l of chemical oxygen demand, whereas for freshly prepared full cream powder milk (Haley, 117.3 gr/l) its contribution was 173,000 mg/l.

For the preparation of synthetic dairy wastewater, powder milk was chosen following Jai Prakash et. al. 2010 [Jai Prakash Kushwaha, et. al. 2010] methodology, but instead the dilution was changed to 2 gr of powder milk per liter.

Analyses such as pH, turbidity, ammonium nitrogen, total solids, total suspended solids, total dissolved solids, BOD, and total and soluble COD (TCOD and SCOD) were also conducted in the lab to characterize the synthetized dairy wastewater, as well as ion traces in search of calcium, potassium, magnesium, iron, sodium, total phosphorous, nitrogen (TKN) and phosphate.

Parameter	Maximum*	Minimum*	Average*
COD	10400	189	3000
BOD	5900	260	1700
pH	11	5.2	7.1 – 8.1
FOG	1920	0.3	0.5
TS	5900	1340	2900
TSS	12500	60	2000
TP	181	0.2	100
PO_4-P	50	0.2	30
T [NTU]	-	-	1744
TKN	430	2	150
NH_4-N	36	5	<10
Na^+	980	170	575
Alkalinity	1200	225	530
K^+	160	8	100
Ca^{2+}	120	1.4	<200
Mg^{2+}	46	2	<400

*Concentration in mg/l except for pH

Table 6.1 Average values in which SDW has to be in between.

Parameter	Haley full cream milk powder [per 11.73gr =100ml]	Almarai full fat fresh milk [per 100 ml]
Protein [gr]	2.87	3.1
Lactose [gr]	4.5	-
Butter fat (min) [gr]	3.28	3.1
Soya Lecithin [mg]	23.46	-
Minerals (Ash) [gr]	0.7	-
Moisture (max) [gr]	0.35	-
Vitamin A (added)	246Iu	200IU
Vitamin D3 (added)	41Iu	40IU
Calcium [mg]	109	100

Table 6.2 Composition per 100 ml of fresh milk and prepared milk with powder milk [Haley and Almarai].

6.1.1 Synthetic Dairy Waste water preparation

Synthetic dairy wastewater was prepared using full cream powder milk (Haley) following the methodology explained by Jai Prakash Kushwaha, et. al. 2010. The choice of powder milk over liquid milk is due to its ease of storage and handling, apart from the fact that whenever it is needed, it can be freshly prepared. Moreover, COD values can be better controlled in this way, as the powder doesn't decay like liquid milk day after day.

In Table 6.3 all the parameters analyzed from the synthetized wastewater are shown, after following the Standard Methods 2005 for every experiment made. The sample was prepared with 2 gr of full cream powder milk in one liter of tap water. The choice of utilizing tap water as the solvent is due to the fact that dairy factories in Saudi Arabia (as in any country) work with tap water. Thus, it is more representative than if distilled water was used.

As seen in the table of concentrations of the synthetic dairy wastewater (SDW) and when compared with the concentrations of the fresh milk as prepared for drinking, it can be inferred quickly that calcium has a high concentration in the SDW. This result, in conjunction with the metal traces analyzed, represents the contribution of ion traces of the tap water itself.

Taking into account the maximum inhibitory concentrations stated in point 3.4.5 and the concentrations obtained in the prepared SDW, all the parameters are within the safe or optimum ranges but sodium.

Parameter	Prepared Concentration [mg/L][1]	Literature Average [mg/L][1, 2]
pH	6.66	7.1 – 8.1
T [NTU]	1500±3	1744
NH_4	<1	<10
TS	1980	2900
TSS	1213	2000
TDS	767	-
BOD	1341±81	1700
SCOD	940±85	-
TCOD	2950±130	3000
TKN	55.72±1.68	150
Ca	227	<200
K	69.4	100
Mg	62.9	<400
Na	511	575
Fe	0.193	-
TP	8.7	100
PO_4^{3-}	6.24±0.24	30

[1]Except for pH and Turbidity. [2]From literature.

Table 6.3 Characteristics of the SDW prepared with powder milk.

Nevertheless, sodium concentration is not high enough so as to produce an adverse effect over the anaerobic bacteria, where this wastewater will be used. The latter can be confirmed by several batch reactors ran at the lab for several months being fed with this SDW in a trial basis. The results were promising, with an increment in the MLSS and biogas production. Thus, this means the SDW that was produced and further shown here is useful for anaerobic biological treatment, which was one of the main objectives of the Independent research prior to the thesis project. Furthermore, the values obtained are within the ranges of concentrations of each parameter according to what it was shown from the literature in Table 6.3.

Concentration of 4 gr of full cream powder milk per liter of tap water can be utilized as well, as the ion traces will not perceive a substantial increase in their concentration, due to the fact that tap water is the main contributor of these ions. This increment of concentration in the powder milk could be done if an increase in COD and BOD values of the feed are to be studied, as it will be done as part of the thesis project. It is worth mentioning, that every 2 gr of powder milk diluted in water, contributes with around 3000 ppm of COD. This relation is useful for when analyzing bacterial behavior at different COD and BOD concentrations.

Overall, some ion traces and major nutrients like iron, are not present in enough amounts to foster bacterial growth, thus an extra addition has to be made in order to meet this requirement. The main compounds that lack in concentration for bacterial growth are phosphorous, magnesium sulfate, calcium chloride, ferric chloride, ammonium chloride and sodium bicarbonate, in small amounts. Table 6.4 shows the concentrations added to the feed on daily basis.

It can be concluded that the synthetized dairy wastewater with the use of powder milk for better handling and storage, was successfully achieved and the concentrations of different parameters obtained are within the range of concentrations published in the literature from different dairy factories in the world.

Compound	Concentration added [mg/l] [1]
NH_4Cl	95.53
KH_2PO_4	10.82
K_2HPO_4	28.06
$NaHCO_3$	300
$MgSO_4$	5
$CaCl_2$	14.6
$FeCl_3$	13.5

[1] Final concentration in the system

Table 6.4 Nutrients added to the feed

6.2 BATCH REACTORS EXPERIMENTS

The initial bacteria inoculation in the bioreactor can be of different nature and the methodology applied could vary as well. Basically there are two ways of starting-up the bioreactor: with seed sludge and without it. Start-up without using any seed sludge (self-inoculum) was feasible within a period of 6-12 weeks at a HRT of around 6 h and psychrophilic temperatures above 20°C [Lettinga G., d et. al. 1993], or around 14 weeks treating raw sewage at 29°C [Kalogo, et. al. 2001]. Also a self-inoculation working in batches was reported to achieve steady state condition within 9 days [Haider M. Zwain, et. al. 2013]. Mainly this practice is not utilized when trying to analyze kinetics or other parameters in a bioreactor because it is time consuming. Therefore, a perusal of the literature indicated that is more feasible, easier and faster the inoculation of seed sludge to the prospective bioreactor. This seed sludge was reported to be taken from full-scale anaerobic wastewater treatment plants [H.E. Grethlein, et. al. 1978, A. Saddoud (b), et. al.2007, D. Martinez-Sosa, et. al. 2011, Yi Jing Chan, et. al. 2012, T.T. Teng, et. al. 2013], including municipal wastewater treatment plants, from the anaerobic liquid drained from a lab-scale thermophilic anaerobic digester of organic fraction of municipal solid waste [W. Charles, et. al. 2009] or seeds developed from previous studies in the lab [W.J. Gao, et. al. 2011, J.A. Alvarez, et. al. 2006]. All of these studies though treating different wastewater and working with different inoculum seed sludge, agreed in that after inoculation for the first time the sludge should be left to rest for 24 h. This rest means no feed is injected to the bioreactor within that time, though mixing is highly recommended in order to

achieve a better acclimation of bacteria to room temperature or working temperature if they differ.

6.2.1 Inoculum study

Two bioreactors were tested with different initial inoculum in order to choose the one with the best performance regarding COD removal and biogas production. The composition of each one and the inoculum bacteria used are described in Table 6.5 as well as other parameters at the initial stage of the experiment. Both bioreactors were ran at the same conditions of temperature, pH (adjusted daily), and feed.

On daily basis pH, MLSS, COD and biogas obtained were noted down for further comparison. Bacteria in both systems were treated the same way from the beginning when being introduced to the system, i.e. they were left to rest for 24 h, as stated hereinbefore with only mixing, and after that period the feed was started. The feed consisted in 50 ml of full fat milk, or its equivalent of 6.9 gr. full cream milk powder, injected to the system every morning. Considering that 50 ml of fresh full fat milk (or its equivalent in powder milk) contributes for around 173,000 mg/L COD, and the reactors volume are 3.5 lt., the organic loading rate (OLR) was around 2500-3000 mg/l day COD.

Daily registries and variations of data such as pH, MLSS, and biogas obtained and COD removal (%) can be seen in Figure 6.1, Figure 6.2 and Figure 6.3, respectively. It can be observed from the graphs that data for the seed yoghurt bioreactor stops on day 17th. This is due to the abruptly stop that this system suffered, with apparently unknown reasons. Whilst the seed sludge bioreactor was working perfectly fine, with

COD reduction and biogas production, and both bioreactors were ran at the same conditions, the seed yoghurt stopped producing biogas abruptly after having worked for 9 days in a row. At the beginning it was thought the system was overloaded, so it was left to rest without being fed and just making pH adjustments to neutral values for 10 more days, with no changes observed at all. One possible explanation for this fact is that MLSS (Figure 6.2b)) showed one peak at the beginning and then decreased till the system halted. Therefore, lack of MLSS is the possible reason that could explain this behavior. MLSS could not be grown with yoghurt as the inoculum seed.

Parameter	Seed sludge Bioreactor (Khobar Wastewater treatment plant)	Seed yoghurt Bioreactor (Almarai Yoghurt)
Working volume	3.5 lt.	3.5 lt.
Initial composition	1.75 lt. activated sludge 1.75 lt. tap water	6 gr. Haley full cream milk powder 80 ml full fat fresh yoghurt (Almarai) 3.5 lt. tap water
Feed (daily)	6.9 gr. Haley full cream milk powder	
pH Adjusters used	NaOH, PO_4^{-3} buffer (pH 7)	

Table 6.5 Parameters of the bioreactors ran at preliminary stage

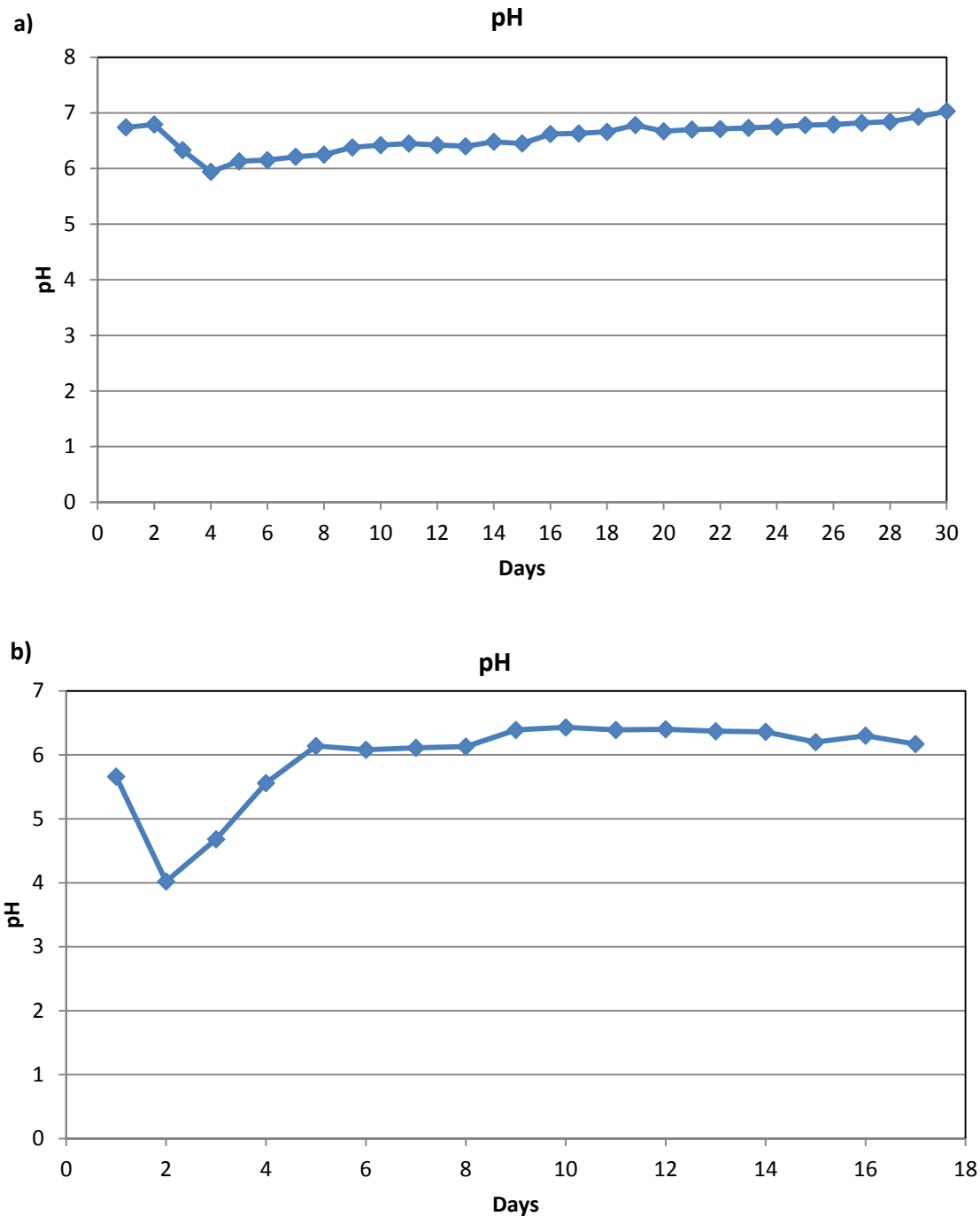

Figure 6.1 pH registry for the a) sludge seed and b) seed yoghurt Bioreactors.

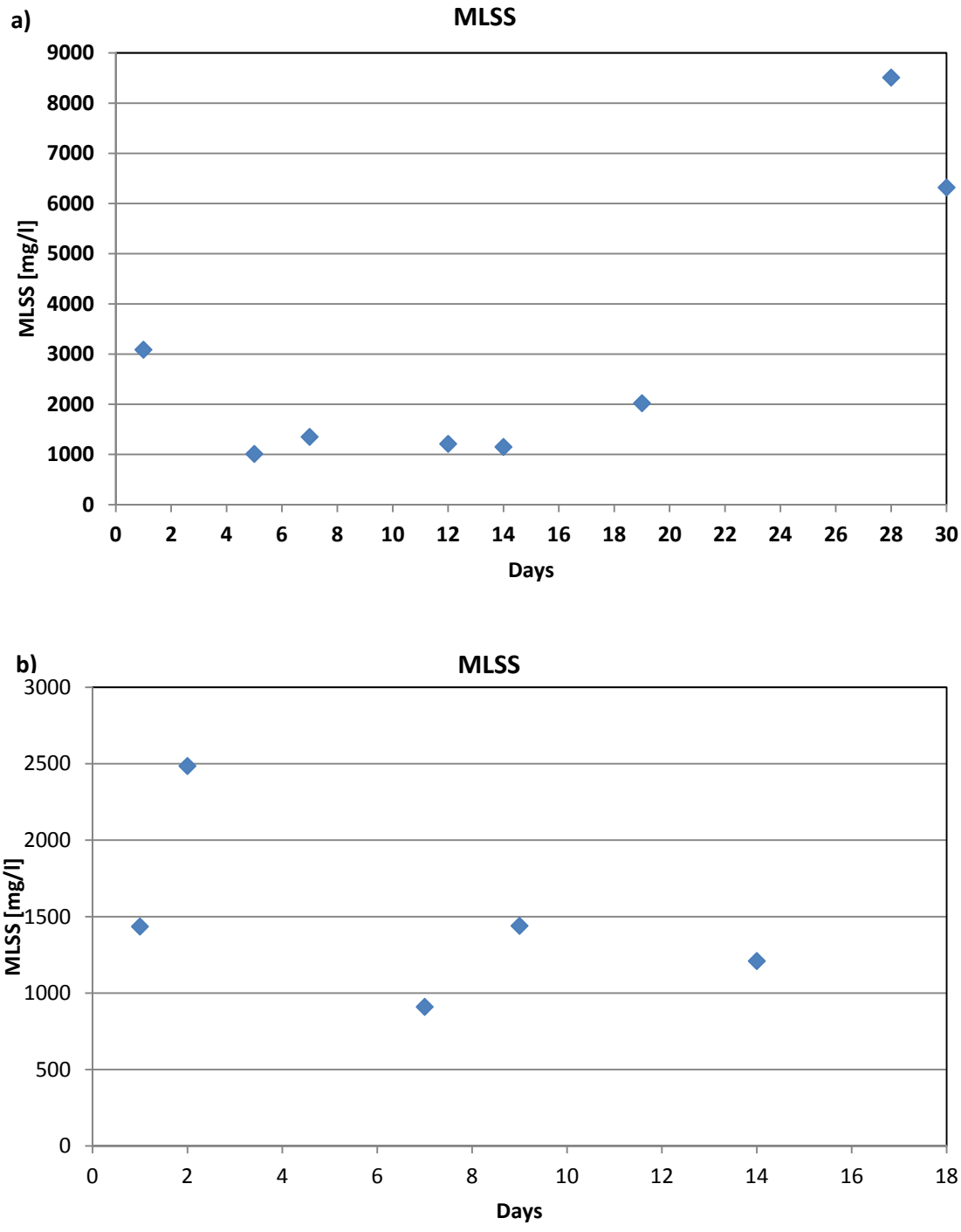

Figure 6.2 MLSS registry for the a) sludge seed and b) seed yoghurt Bioreactors.

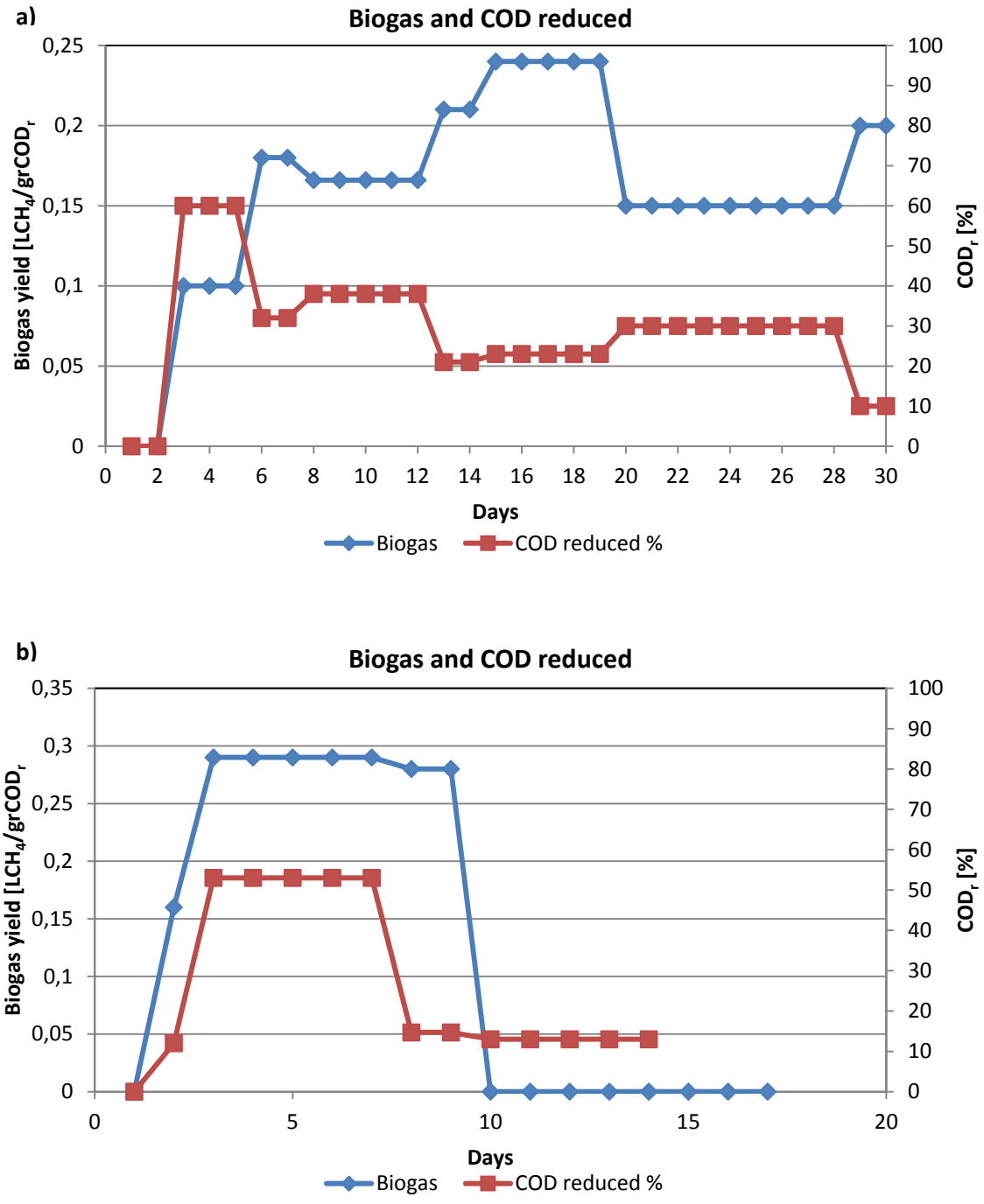

Figure 6.3 Biogas and COD reduced (%) registry for the a) sludge seed and b) seed yoghurt Bioreactors.

6.2.2 Analysis and inoculum selection

Both bioreactors tested showed an abrupt pH decrease within the first 4 and 2 days for the seed sludge and seed yoghurt, respectively. It can be inferred from Figure 6.1 that this behavior is common whichever the seed for inoculum is used, and after that lag period pH could be restored closer to neutral values. On a daily basis pH was adjusted (every morning) to neutral values within the range 6.8-7.5, using 2.5 N NaOH. Reluctance to pH change was more marked on the seed sludge bioreactor than the seed yoghurt, as it can be seen from Figure 6.1a). Around 30 days were necessary for the seed sludge bioreactor to reach steady state conditions regarding pH values, after which NaOH was added in less amounts.

Regarding MLSS, the seed sludge bioreactor showed a better response with an increment of MLSS after 20 days, as shown on Figure 6.2. During the first 20 days period MLSS was almost constant with not much variation observed. The peak on day 28 of 8510 mg/l of MLSS could be the response of phosphate addition to the system, which comprises a nutrient, after which the system was left to rest without addition of feed, and biogas production was observed.

Biogas yielding in both bioreactors showed a trend to increase at the beginning giving high values till the system was stabilized (Figure 6.3 a and b), and the same happened with COD reduction. The seed yoghurt bioreactor in this matter showed a great response with values around 0.29 l/g. COD_r and 50%, for biogas yield and COD removal, respectively, whereas for the seed sludge bioreactor these values reached an average of 0.16 l/g. COD_r and 30%, for biogas yield and COD removal, respectively.

Despite these differences between both systems, the seed yoghurt system halted after day 9 showing no biogas production and dropping COD reduction to less than 10%, whereas the seed sludge bioreactor kept these values constant.

For what it was exposed hereinbefore, seed sludge inoculum was chosen for the start-up of the bioreactor to treat the synthetized dairy wastewater proposed. Furthermore, the same batch bioreactor was injected as inoculum to the bioreactor for the thesis, which comprised a volume of 22 liters. Thus, around 18% of the total volume of the bioreactor was filled by the inoculum bacteria. This practice was shown to be enough for the start-up of the system [Yi Jing Chan, et. al. 2012], plus the bacteria in this case were already stabilized to high organic loading rate and the same feed.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 BIOREACTOR PERFORMANCE

Immediately after the 30-days stabilization stage the sludge chosen (seed sludge) was injected in the system which comprised a volume of 22 liters and, as stated before, it was left to rest for 48 h (Acclimation to the new environment), after which the feed began to be injected and the whole system was started up. Nutrients such as phosphate, calcium chloride, magnesium sulfate and calcium bicarbonate were still injected into the system during the whole experiment. For another 30-days period the system was fed with a concentration of 2000 ppm of COD on a daily basis for further acclimation. After all this period of 2 months analyses of the system started.

The system started at 10,000 mg/l MLSS following the pre-set COD concentrations, starting at 2000 ppm. Because the system had been ran for 2 months with good acclimation and response to the feed, and the COD concentrations were increased step wised, was that steady-state points were achieved with success. It is worth mentioning that MLSS concentration played a big role for achieving the mentioned points.

7.1.1 Hydraulic Performance

In order to maintain stable conditions and be able to study the biokinetics of an anaerobic membrane bioreactor of one phase, all the hydraulic parameters controlling the system were set. Thus, the main component ruling the steady-state conditions is the concentration of MLSS, which can vary according to the HRT, SRT and OLR implemented to the system. Therefore, a fluctuation in the MLSS concentration could cause system instability until it is taken back to stable conditions.

During the whole experimental work for MLSS concentrations of 5,000 mg/l, 10,000 mg/l and 15,000 mg/l, HRT was kept as constant as possible presenting minor fluctuations according the flux and membrane pressure variation. Figure 7.1, Figure 7.2 and Figure 7.3 show the variation of flux, HRT and membrane pressure for the different MLSS concentrations, respectively. The transition phase that is observed in every graph refers to the time when the system was left to increase its MLSS concentration to continue with the following stage. Nonetheless, this phase is not seen between the 5000 and 10000 mg/l concentrations due to the fact that the former, chronologically speaking, was ran after the 15000 mg/l, but it was drew as the first stage in order to better observe the trends the system follow at increasing MLSS concentrations.

Flux varied between 2.07-2.29 l/m^{2}hr representing a minor fluctuation with an average of 2.20 l/m^{2}hr, 2.22 l/m^{2}hr and 2.18 l/m^{2}hr for MLSS concentrations of 5,000 mg/l, 10,000 mg/l and 15,000 mg/l, respectively. These values are low, but when compared with the literature which vary from 1,8 l/m^{2}h to more than 100 l/m^{2}h [B.E.L. Baeta, et.

al. 2012, D. Jeison (b), et. al.2008, J. Zhang, et. al. 2007], it can be said that the flux was within the values used in investigations. This flux stability helped to keep HRT as constant as possible as it can be observed in Figure 7.2, where it varies between 10-11 days. HRT values can range from a few hours (2 hr) [J. Kim, et. al. 2011] to a few days (14-20 d) [E. Jeong, et. al. 2010], and even for long periods of 40-60 days [Tjoon Tow Teng, et. al. 2013]. It is worth mentioning that it is a well-known fact that the flux will vary according to the membrane pressure, which varied between a narrow though high range of 12.77-13.63 psi, 12.52-13.14 psi and 11.30-13.51 psi for the concentrations of 5,000, 10,000 and 15,000 mg/l MLSS, respectively. The pressure drop on day 67 was due to a leakage in the pump hose. The pressure obtained in other experiments ranged from under 0.1 psi to 15 psi (maximum) for tubular membranes [A. Akram (b), et. al.2008].

Membrane pressure and turbidity are strictly linked to membrane fouling. Thus, high fouling is responsible of high pressure but could decrease turbidity because of cake layer formation at the beginning. The latter fluctuated within a narrow high range 11.7-25.7 NTU for the 10,000 mg/l MLSS concentration, as shown in Figure 7.4, with an average of 20.59 NTU. During the stage of 15,000 mg/l MLSS the turbidity shows an increasing trend with the increase of the COD concentration in the feed with an average of 15.36 NTU, shown in Figure 7.4, showing an improvement at higher MLSS concentrations. Due to the fact that to prepare a feed with higher COD concentration the synthetized dairy wastewater has more milk particulates in it that can go through the pores of the membrane, when increasing the COD concentration in the feed an increase in the turbidity is expected.

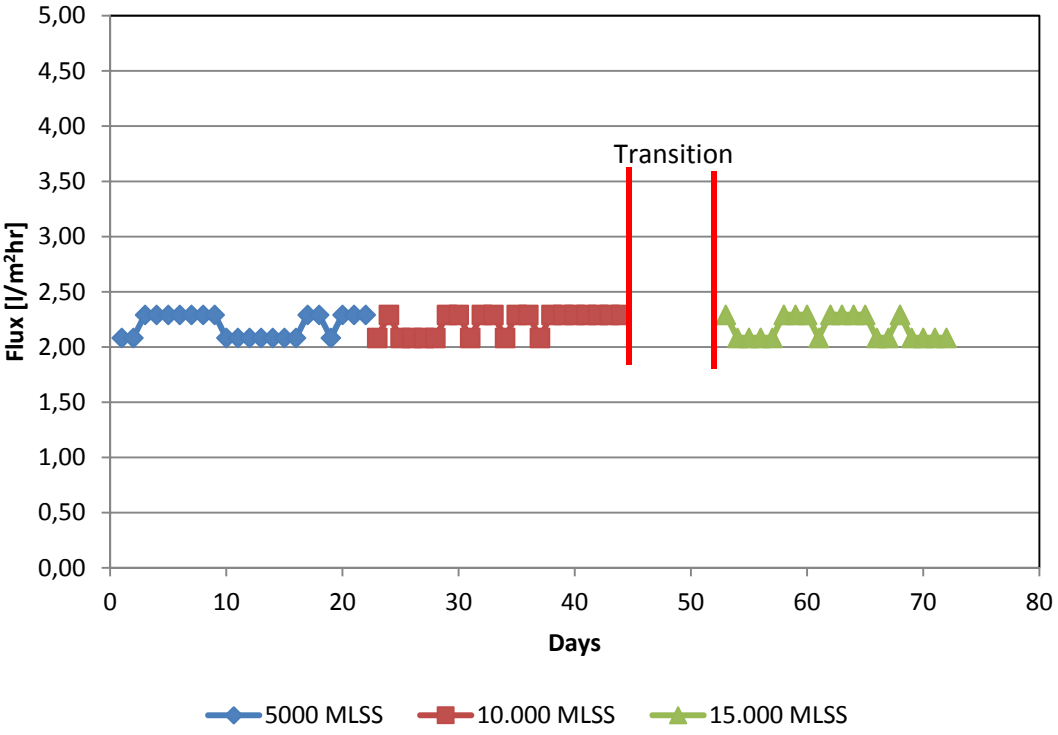

Figure 7.1 Variation of flux with time for 5,000, 10,000 and 15,000 mg/l MLSS

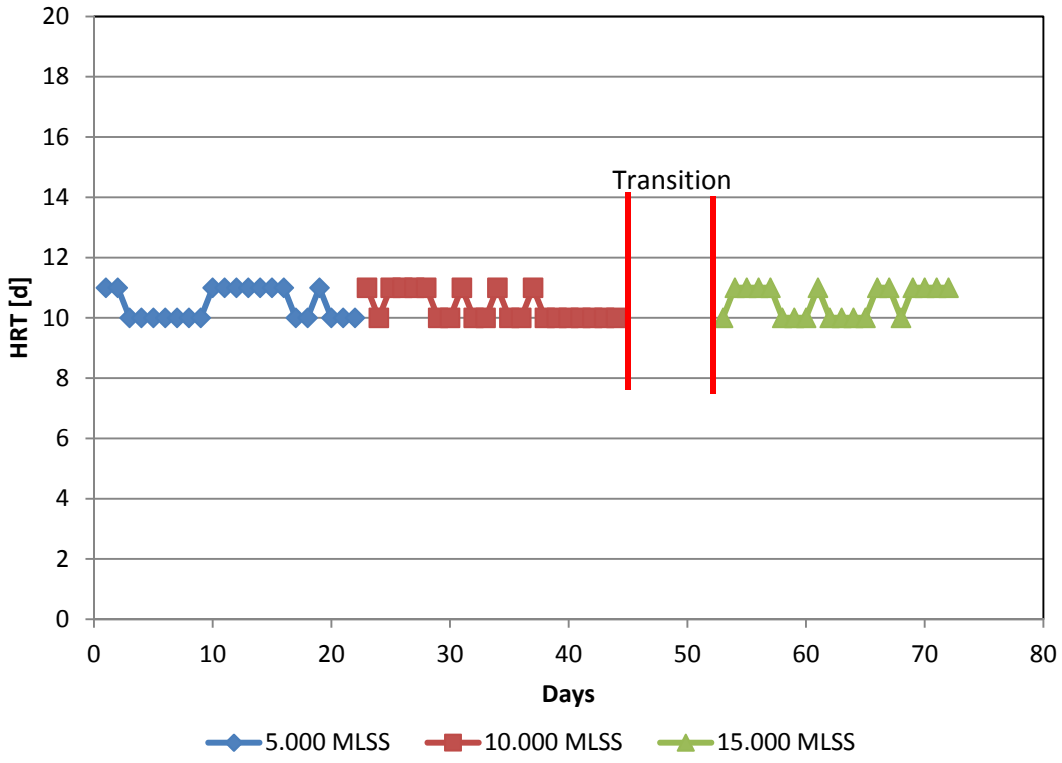

Figure 7.2 Variation of HRT with time for 5,000, 10,000 and 15,000 mg/l MLSS

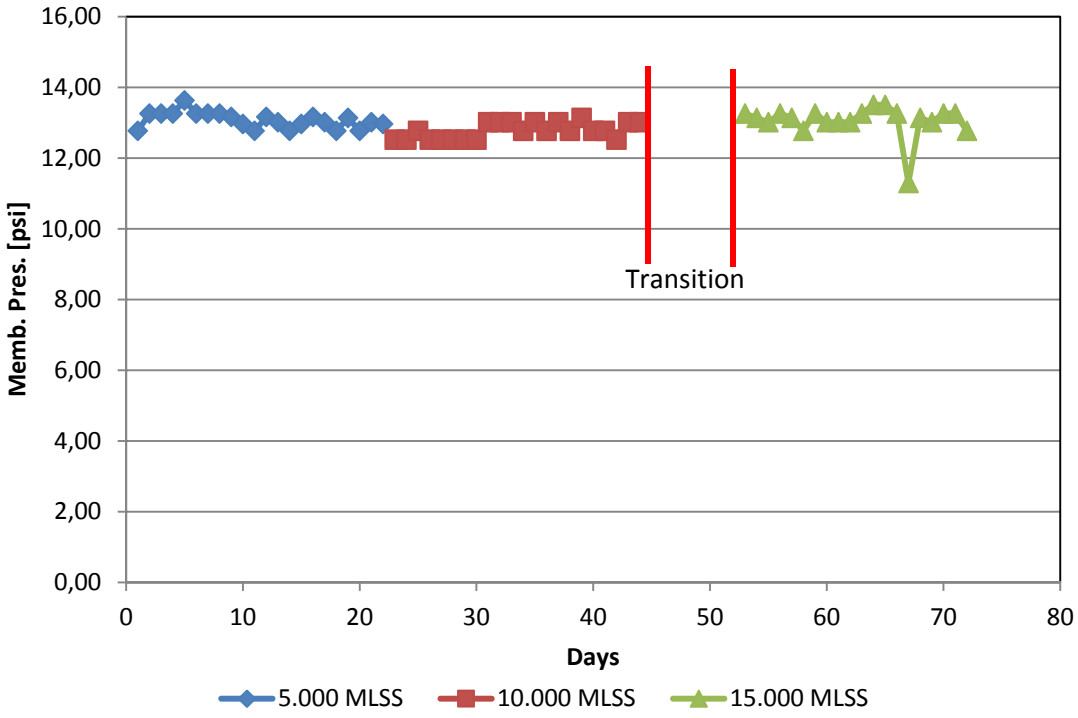

Figure 7.3 Variation of Membrane pressure with time for 5,000, 10,000 and 15,000 mg/l MLSS

In spite of this, the phenomenon could not be observed when working at 10,000 mg/l MLSS concentration. Figure 7.4 is also showing turbidity at 5,000 mg/l of MLSS concentration. As stated hereinbefore at lower MLSS concentrations turbidity is expected to be higher, as it was in this case, fluctuating in a range of 20.1-159 NTU with an average of 48.87 NTU. The peak obtained in day 2 was due to high membrane fouling which, after chemical cleaning, the turbidity dropped down again to stable values. Nitric acid with pH above 2 was used for this purpose. The turbidity obtained in a lab-scale experiment performed by A. Saddoud (a), et. al. 2007 treating cheese whey was in average 14.5 NTU in the permeate, which concords with the turbidity obtained in this experiment for the last two stages. Values from 2.3 to 226.0 NTU were obtained in a two-phase anaerobic system coupled with a filtration unit and varying the operational conditions, conducted by Vera Mota. et. al. 2013 treating stillage. The presence of micro-colloidal compounds in the range of 0.01-0.03 μm, can explain the high values obtained in the first stage of the experiment, i.e. at 5,000 mg/l MLSS. Moreover, considering that the synthetic wastewater used in this experiment had a turbidity greater than 1500 NTU, the removal efficiency was always above 98.6% for the last two stages, and above 94.63% in the first stage.

In Figure 7.5 the pH variation during the whole experiment is shown. Mainly it was kept strictly stable between 6.8 and 7.2 though during the first stage when 8000 ppm COD was injected as the feed at 5000 mg/l MLSS, it tended to drop down to values around 6.70. In order to keep pH values within the optimum range, 2.5 N NaOH solution was used to raise the pH up again, basically on daily basis. When the values were above 7, there was no alkalinity addition during that day.

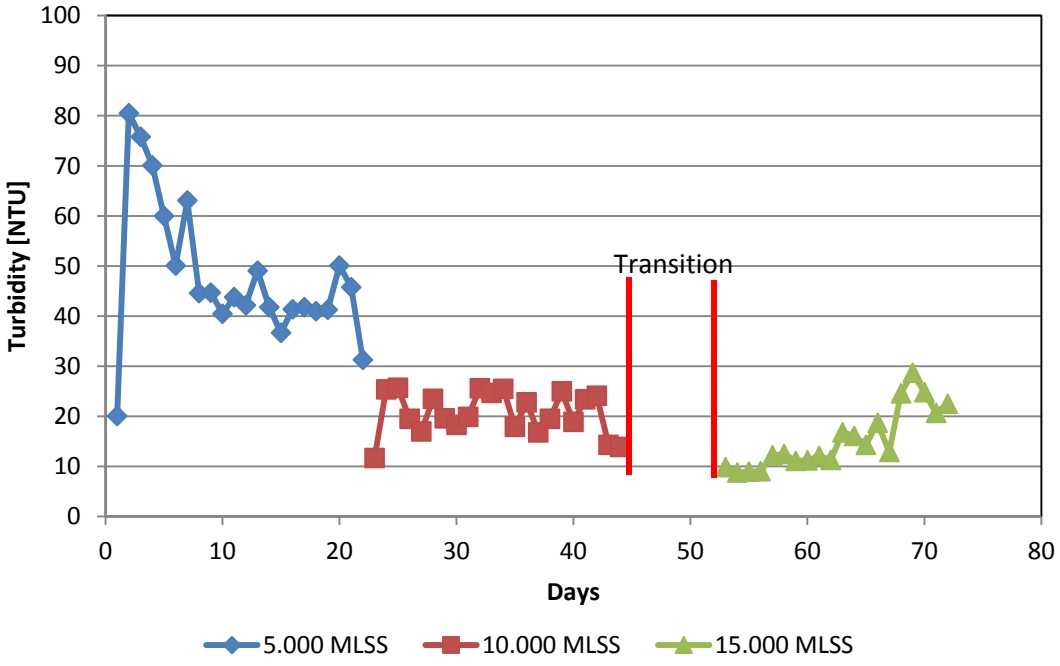

Figure 7.4 Variation of turbidity with time for 5,000, 10,000 and 15,000 mg/l MLSS

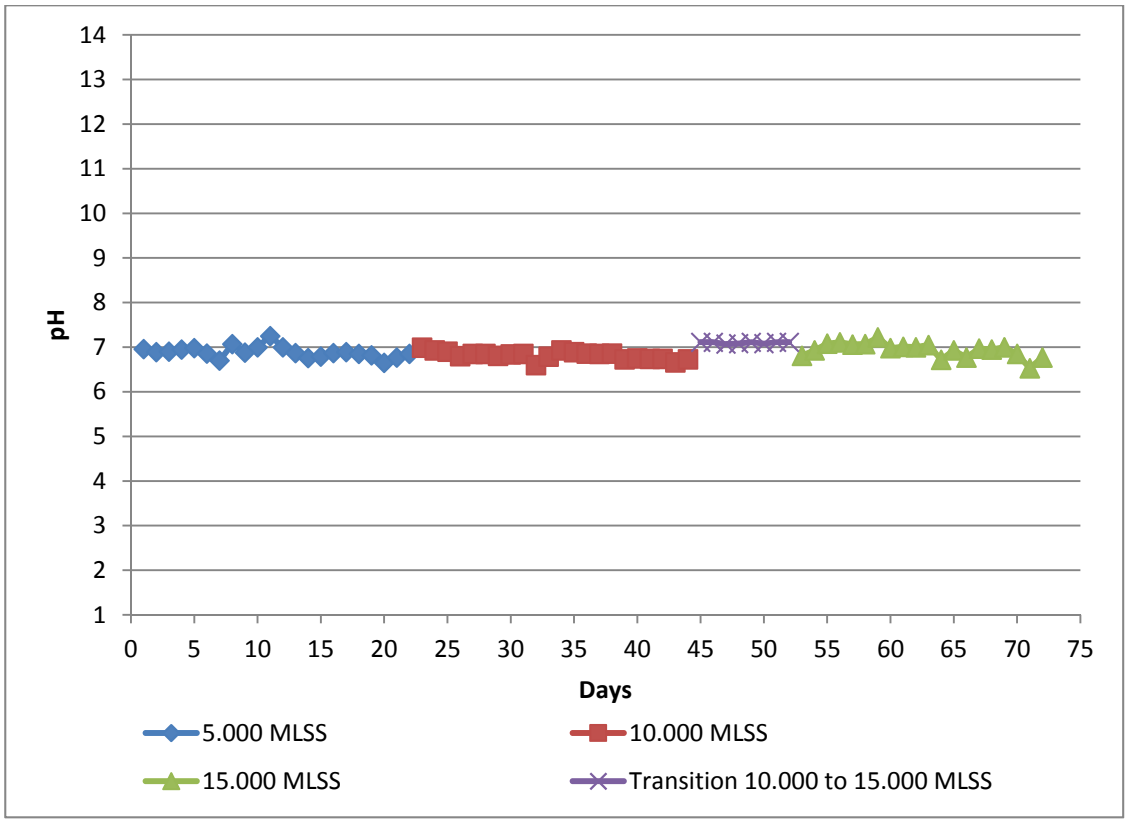

Figure 7.5 pH variation with time

7.1.2 Biogas yield and COD removal performance

To assess the performance of the SAnMBR treating synthetized dairy wastewater, both COD removal efficiency and biogas production have to be measured at different OLR and MLSS concentrations, and a combination of them.

The starting point concentration of MLSS was 10,000 mg/l, then varying the OLR from 2000 to 8000 ppm COD stepwise. The following point was tested at 15,000 mg/l of MLSS and finally dropping it down to 5,000 mg/l of MLSS. After each increase of the OLR the effluent COD arose as well during all the stages but presenting a fairly stable removal (Figure 7.6). During these phases of OLRs, COD removal was measured as a control parameter of the reactor efficiency, as shown in Figure 7.7 for concentrations of 5,000 mg/l, 10,000 mg/l and 15,000 mg/l MLSS.

Investigators have tested different wastewaters with concentrations of COD ranging from as low as 162 mg/L [Y. An, et. al. 2009] to 10,000 mg/L for kraft evaporator condensate [H.J. Lin, et. al.2009] or even 18,000 mg/L for a petrochemical effluent with high-strength composed by short-chain fatty acids [P.J. Van Zyl, et. al. 2008]. Thus, the COD values of the influent used in this experiment were within the values of dairy wastewater effluents as stated in point 6.1 before.

At a MLSS concentration of 10,000 mg/l during the first three phases, when the influent COD was 2000, 4000 and 6000 ppm, average COD removals were 83.2%, 86.4% and 83.9%, respectively. Interestingly when the OLR was increased to 8000 ppm the removal decreased to an average of 74.2%, thus the sharp jump on the effluent COD on Figure 7.7. This trend has appeared from the previous stage of 6000 ppm,

though the removal decrease was not that sharp. In this stage the maximum COD removal was 86.4% with an OLR of 4000 ppm COD.

At a MLSS concentration of 15,000 mg/l the trend is almost repeated as with the previous MLSS concentration, with a sharp jump when the OLR of 8000 ppm was given as feed (Figure 7.7). However, in this stage of MLSS concentration the COD removal was within a narrow range between 88.4% and 91.4% for the first three phases of COD concentrations, and dropped to 79.8% at the last COD concentration of 8000 ppm. In this stage the maximum COD removal was 91.4% with an OLR of 4000 ppm COD.

When the MLSS concentration was dropped down to 5,000 mg/l the COD removal, shown in Figure 7.7, was in average low and still presented a jump when it was fed with 8,000 ppm of COD concentration. This could be an indicative that this bacteria which were grown in the experiment were not able to cope with this concentration thus the instability and drop-down of the system efficiency. COD removal in this stage was kept between 47.5% and 55.8% during the first three phases of COD concentrations, and 37.3% at 8,000 ppm. In this stage the maximum COD removal was 55.8% with an OLR of 6000 ppm COD.

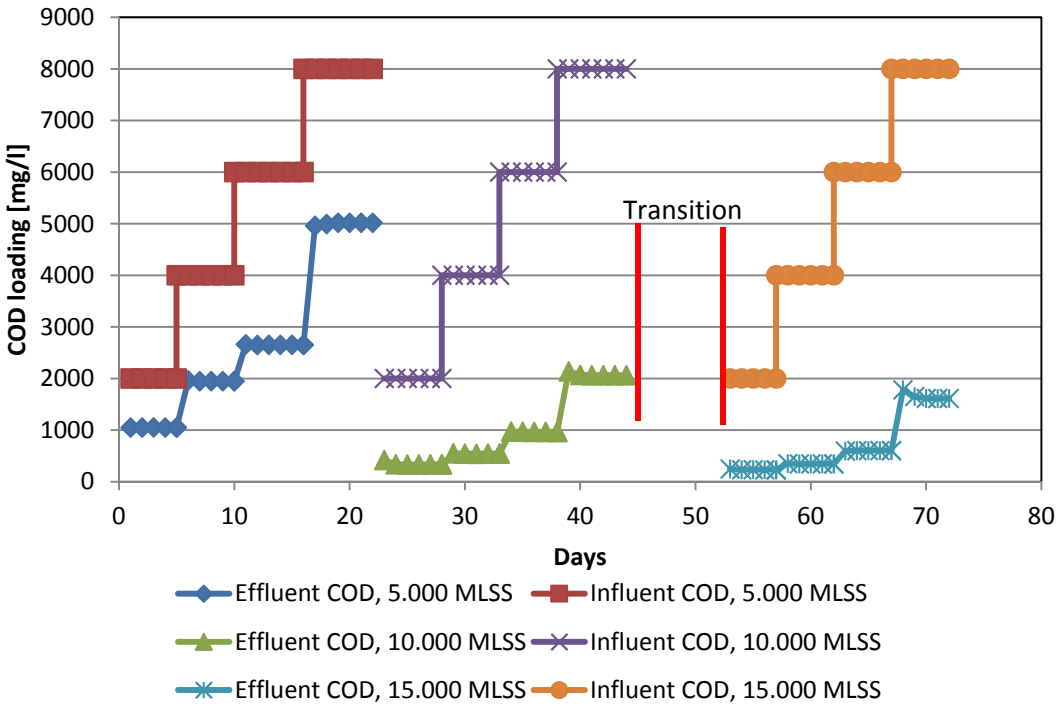

Figure 7.6 Variation of influent and effluent COD at 5,000, 10,000 and 15,000 mg/l MLSS

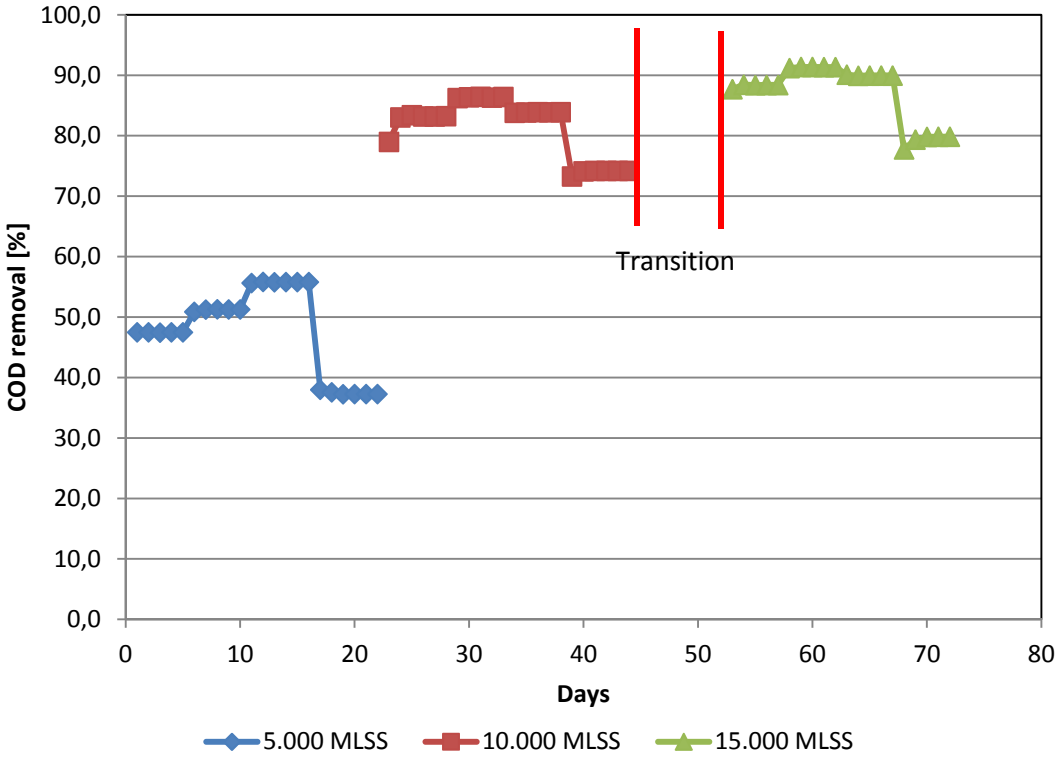

Figure 7.7 COD removal efficiency with time at 5,000, 10,000 and 15,000 mg/l MLSS

Removal efficiencies in other studies have varied from 76% [A. Saddoud, et. al. 2006] up to 99% [Z. Huang, et. al. 2008, H.J. Lin, et. al.2009]. Haider M. Zwain et.al. 2013 reached to a maximum COD removal of 71% in continuous mode treating recycled paper mill wastewater. Therefore, the values obtained in this experiment are in accordance with other studies.

While the best efficiency at 10,000 mg/l MLSS regarding COD removal was achieved at 4000 ppm COD, for biogas yield it was at 2000 ppm COD as it can be seen from Figure 7.8, with a yield of 0.17 L/grCOD_r and a methane concentration of 29%. On the other hand, at 15,000 mg/l the best efficiency for biogas was during both 4000 ppm and 6000 ppm COD as shown in Figure 7.8, with a yield of 0.18 L/grCOD_r and a methane concentration varying between 62% and 82%. At 5,000 mg/l of MLSS the biogas efficiency was almost regular presenting minor fluctuations between 0.066-0.104 L/grCODr, though it was low (Figure 7.8) with an average of 0.088 L/grCOD_r and a methane concentration varying between 16% and 24%. The two peaks of 0.066 and 0.104 L/grCOD_r were obtained during the COD concentrations of 4,000 and 8,000 ppm, respectively.

In spite that the higher the OLR the higher the biogas production, at the last phase of 8000 ppm at 10,000 mg/l of MLSS the system responded with less efficiency (Figure 7.8 and Figure 7.9). During 4000 and 6000 ppm COD phases the biogas yield was kept roughly constant at 0.15 L/grCOD_r, dropping then to 0.10 L/grCOD_r. The total gas obtained during this stage was 30.3 l (Figure 7.9).

During the MLSS concentration of 15,000 mg/l the biogas yield behaved quite different from and more stable than the previous stage (Figure 7.8 and Figure 7.9). During 2000 and 4000 ppm phases of COD concentration, the gas yield was almost constant around 0.18-0.19 L/grCOD_r, while in the last two phases, 6000 and 8000 ppm COD, it dropped a little and staying fairly constant at 0.17 L/grCOD_r. The total gas obtained during this stage was 35.56 l (Figure 7.9).

At 5,000 mg/l of MLSS the biogas yield was fairly regular with minor fluctuations as stated above. The drop-down trend that was observed in the previous stages of 10,000 and 15,000 mg/l MLSS at the 8000 ppm COD phase was not sharply marked in this stage, on the contrary a peak of biogas yield was obtained during that phase of 8,000 ppm COD (Figure 7.8). The total gas obtained during this stage was 21.29 l (Figure 7.9).

The observed methane yield in several studies ranged from 0.003-0.33 L.CH_4/g COD_r, and a methane concentration varying between 55-90% [Haider M. Zwain et. al. 2013, H. Lin (b), et. al. 2011, A. Saddoud (a), et. al.2007, A. Saddoud (b), et. al.2007, J. Ho, et. al. 2009, A.Y. Hu, et. al. 2006, D. Martinez-Sosa, et. al. 2011], which is a bit lower from the theoretical yield of 0.382 L.CH_4/g COD_r at 25°C. These values can be due to methane solubility [N. Brown, et. al. 2006], which is highly dependent on the operational temperature, and to some inhibitors associated with the anaerobic process [Y. Chen, et. al. 2008] such as organics, sulfide, ammonia, light and heavy metal ions. Solubility of methane is around 1.5 times higher at 15°C than at 35°C for a regular 70% methane content on the biogas.

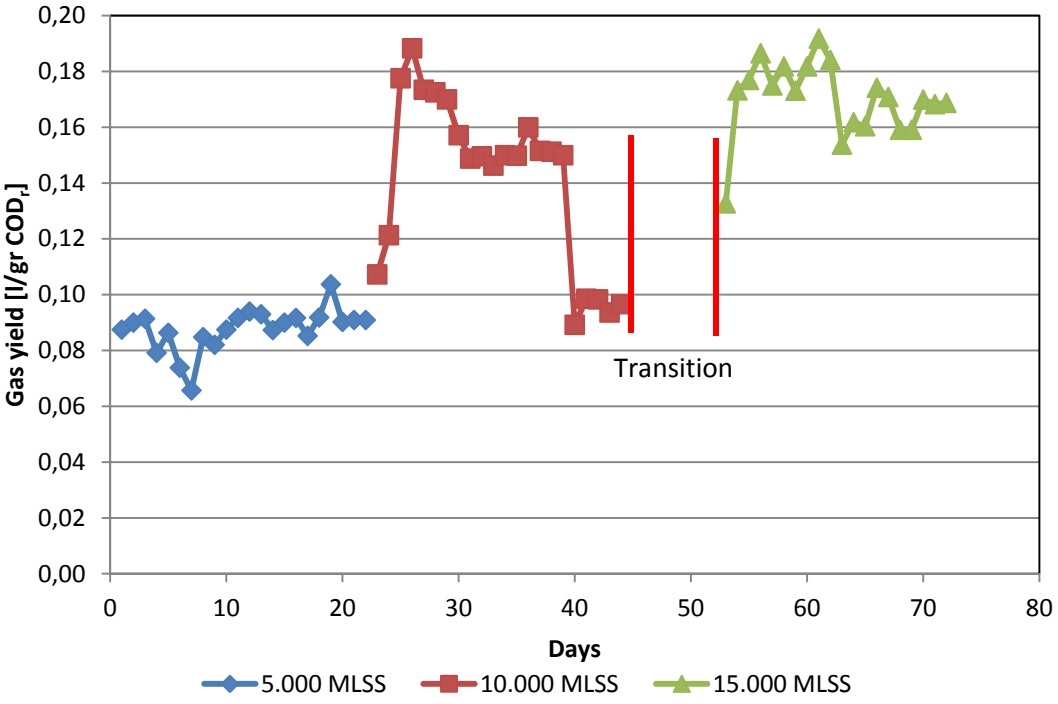

Figure 7.8 Biogas yield variation with time at 5,000, 10,000 and 15,000 mg/l MLSS

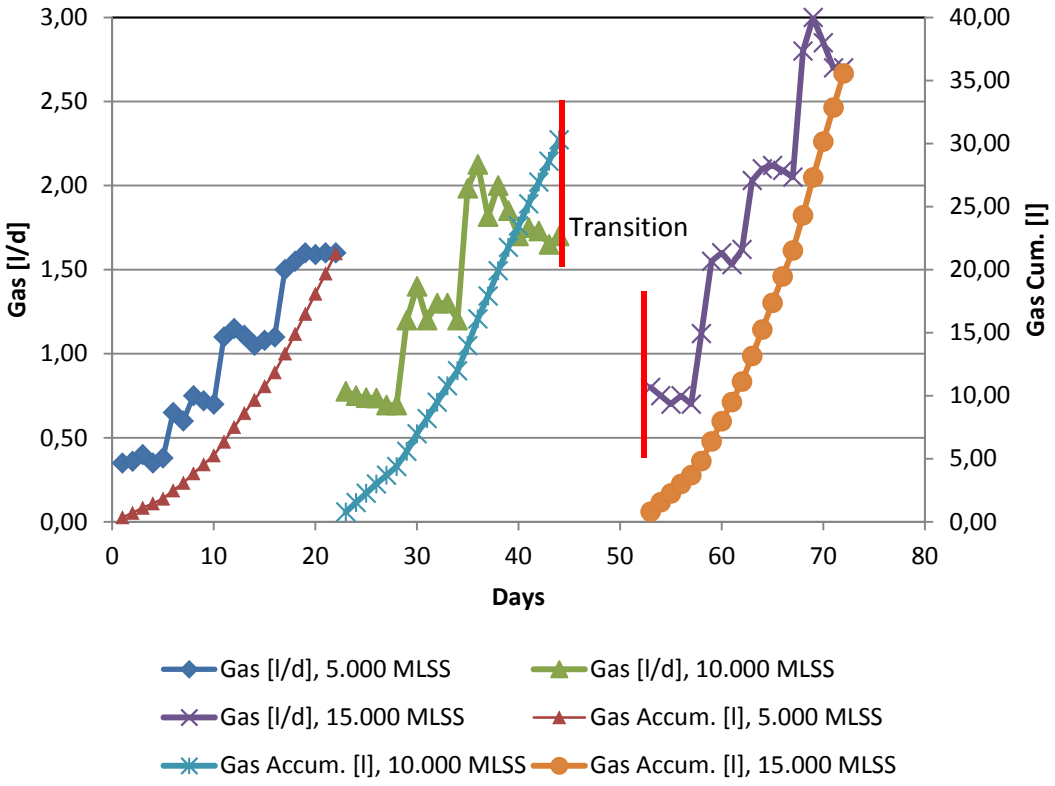

Figure 7.9 Biogas production per day and cumulative with time at 5,000, 10,000 and 15,000 mg/l MLSS

If the previous figures are observed, biogas production follows a trend of increasing with increasing MLSS concentrations as it was expected and supported by other experiments [Chiu-Yue Lin, et. al. 1990; Yee-Shian Wong, et. al. 2014]. This is shown in Figure 7.10 in order to depict a better relation between the total biogas produced and the concentrations of MLSS in the experiment. Due to the fact that each stage of MLSS concentration had a different behavior during the experiment, and that steady-state conditions were attained at different times, is that not all the stages were ran for the same amount of days. Thus, for the values of total biogas to be comparable between each other, a 15-days period was considered taking into account only the first 3 phases of COD at each MLSS concentration.

At the set conditions of the experiment (i.e. fixed concentration of nutrients, same variation of OLRs, fixed temperature, HRT and pH), an increase in the MLSS concentration will increase the biogas production. This trend cannot be infinite if the set conditions are not modified, due to the fact that the system will reach a point where all the substrate has been consumed and the maximum biogas production would have been attained. From there on if the MLSS concentration is further increased, biogas production will reach a "plateau" where after it no increase in the biogas will be observed as shown in Figure 7.10. At this point, 100% substrate removal efficiency will have been attained (theoretically).

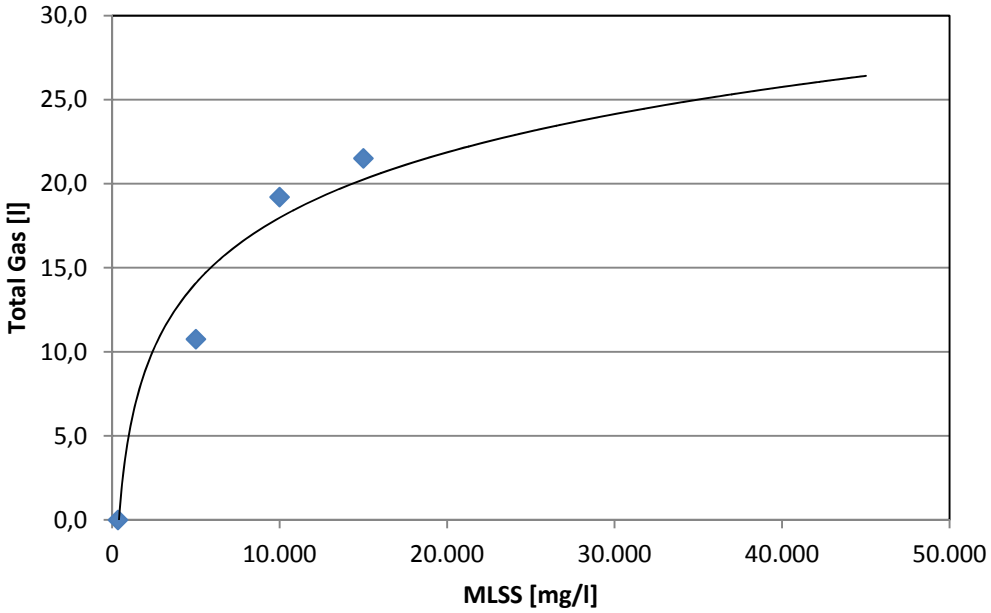

Figure 7.10 Total Biogas produced during each stage of MLSS concentration, considering 15 days of operation.

An analysis in deep of gas production was made and presented in Figure 7.11, in order to investigate the relation between daily biogas production and MLSS concentration at fixed OLRs. As stated before, for a certain OLR, biogas production increases with the increase in biomass. The trend is observed for the different OLRs tested. Furthermore it can be observed that when increasing the OLR the biogas production also presents an increase [Chiu-Yue Lin, et. al. 1990; Yee-Shian Wong, et. al. 2014], but at one point of the graph (10,000 mg/l MLSS and 8,000 ppm COD), which is supposed to be higher. This behavior was attributed to a leakage in the biogas collection system as on the other two MLSS concentrations it was observed that the biogas production increased continuously with an increase in the OLR. Therefore, the dashed line represents the biogas production with the data gathered, and the continuous line represents a conservative estimate for the trend that it should have been observed.

To get a better insight of the biogas production trend when increasing the OLR at a fixed MLSS concentration, Figure 7.12 is presented. It clearly shows that for any MLSS concentration, biogas production increases with the increase of OLR. It also presents an increase when working at higher MLSS. Nevertheless, when comparing the MLSS of 10,000 and 15,000 mg/l, the daily biogas obtained did not vary significantly as when comparing 5,000 with 10,000 mg/l MLSS. Thus, if the MLSS continues increasing the biogas will not present higher values. This can be explained by Figure 7.10 when the "plateau" is reached a further increase in MLSS will not produce better results, if working at the set conditions. The dashed and continuous trend lines follow the same explanation for the previous figure.

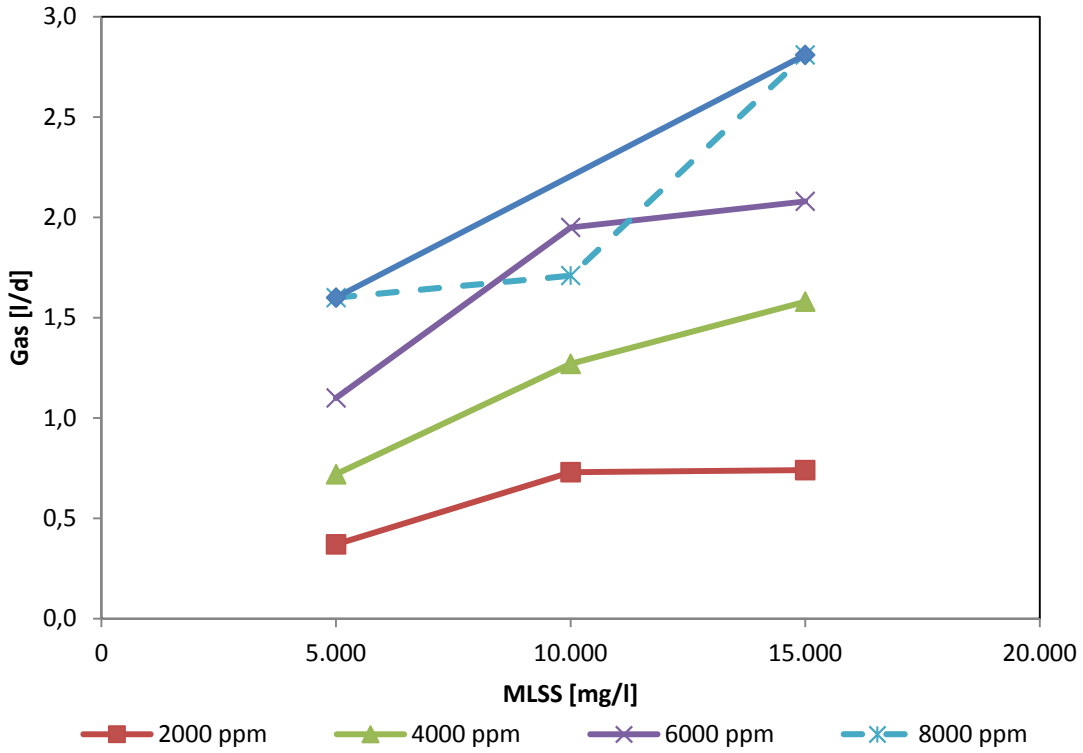

Figure 7.11 Variation of biogas production per day at different MLSS concentrations and fixed OLRs.

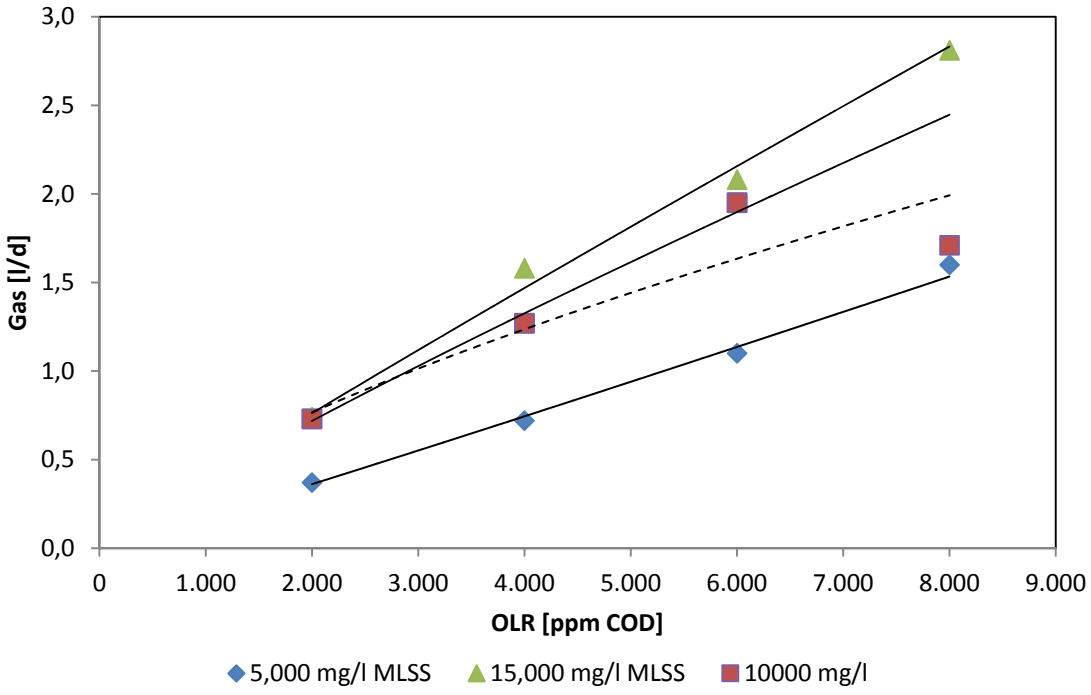

Figure 7.12 Variation of biogas production per day at different OLRs and fixed MLSS concentration.

In Figure 7.12 it can be observed as well the point (10,000 mg/l MLSS; 8,000 ppm COD), where the biogas production was affected as it was the first time the system received such an organic load. The other two points at 8,000 ppm COD describe better the trend, and it can be confirmed that the methanogenic consortia was well settled and could overcome the shocking load, thus producing more biogas.

The trend lines selected for Figure 7.10 and Figure 7.12 are represented by a logarithmic and a power equations, respectively. The first curve better represents the biogas production when the MLSS increases and the substrate is kept constant, presenting an exponential phase, a maximum phase and a flat phase. On the other hand, the power equation for Figure 7.12 could be replaced by a linear equation, but as it is representing a microorganisms' relationship and they do not follow a strict trend (they are affected by several factors), it cannot be a linear relation.

To keep a more stable condition within the system, as stated several times, proper care was taken at maintaining constant MLSS concentrations. Though the cell growth was very slow, as it is an anaerobic system, the need to waste some part of the sludge was still there. Figure 7.13, Figure 7.14 and Figure 7.15 show the fluctuation of MLSS and SRT for the MLSS concentrations of 5,000 mg/l, 10,000 mg/l and 15,000 mg/l, respectively. SRT presented a variation from 60 to 500 days during all the stages. Values of the sludge retention time vary widely from as low as 20 days to 300 days or infinite [G. Skouteris et. al. 2012], which means there is practically no sludge wastage.

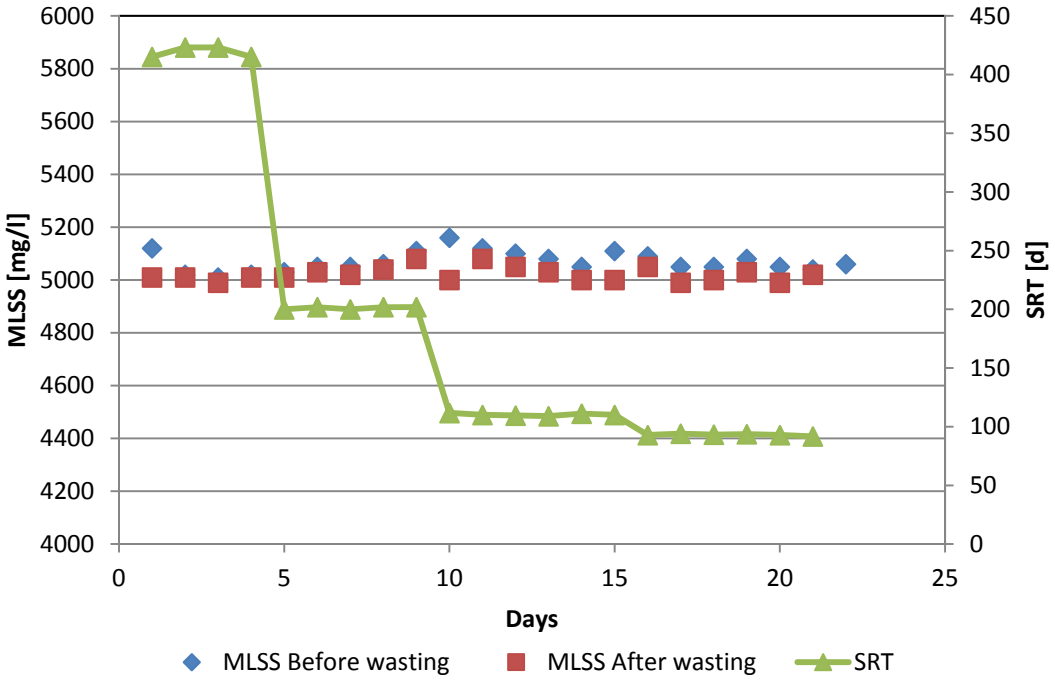

Figure 7.13 MLSS concentration and SRT fluctuations with time at 5,000 mg/l MLSS

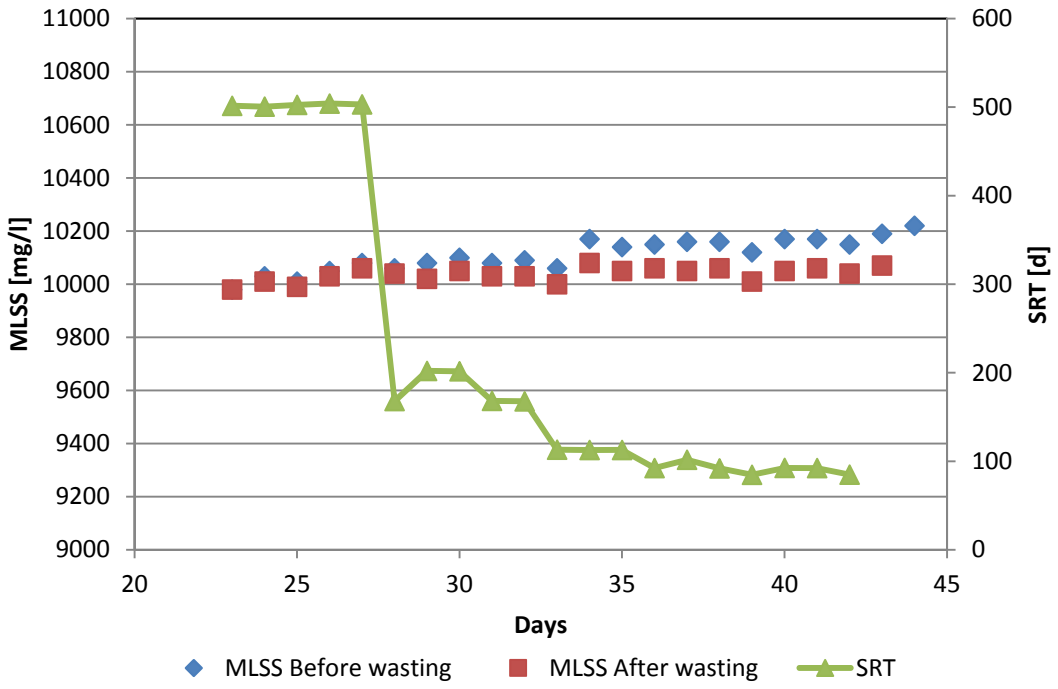

Figure 7.14 MLSS concentration and SRT fluctuations with time at 10,000 mg/l MLSS

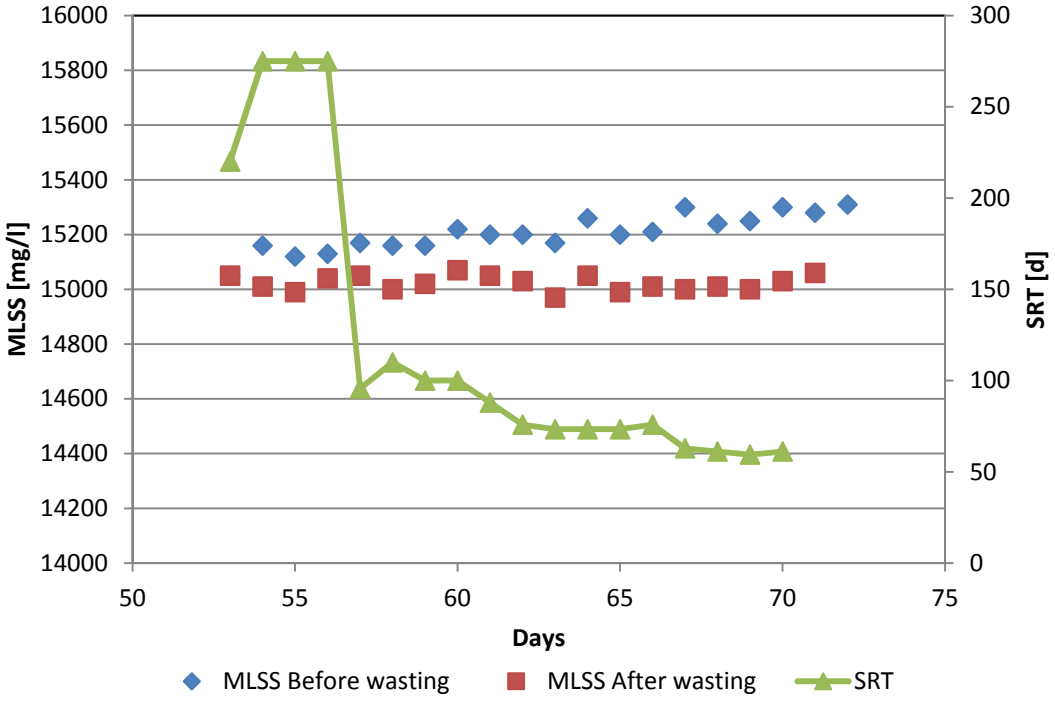

Figure 7.15 MLSS concentration and SRT fluctuations with time at 15,000 mg/l MLSS

Sludge production rate is one another way to determine the growth rate of the bacteria. Figure 7.16 shows this in terms of ΔMLSS/ΔCOD [mg/mg] during the whole experiment. As observed, values range from 0.007 to 0.056 mg MLSS/mg COD with an average of 0.0224 mg MLSS/mg COD indicating that the need for sludge production to tackle down the COD is low. This goes in accordance to anaerobic wastewater treatment principles as the sludge production is low, and it requires less quantity of MLSS to reduce the same amount of COD when compared to aerobics. Values in the literature support the results obtained in this experiment, varying from 0.02 mg MLSS/mg COD when treating mill wastewater [Habets, et. al. 1991, Nilsson, B., et. al. 1994], to 0.1 mg VSS/mg COD [Xiaoxia Li, et. al. 2014].

Figure 7.16 shows a marked increasing trend of the sludge production rate when increasing MLSS concentrations. At the first two stages of the experiment, i.e. at 5.000 and 10.000 mg/l MLSS, the sludge production rate is kept constant around 0.14 and 0.2 mg MLSS/mg COD removed. This can be explained due to the fact that bacteria were able to reproduce freely while consuming the nutrients in the feed and reducing COD values. It could be thought that the more substrate and nutrients in the feed, the more bacterial growth, and actually it is true to a certain extent because when MLSS concentrations are increased, the free space between bacteria is reduced and therefore the easy access to nutrients and substrate is modified, leading to a non-linear relation between the weight of sludge produced and the weight of COD removed or consumed by the process. This is exactly what happened when MLSS concentration was set at 15.000 mg/l, yielding higher sludge production than in the other two stages of MLSS

concentrations, which can be attributed to the complexity of the process that is taking place in a mixed culture bioreactor where many factors can affect the efficiency.

An analysis of the effect of SRT and OLR on sludge production rate was performed and shown in Figure 7.17, where it can be observed that the sludge production rate decreased with increasing SRT and OLR values. It could be thought that an increase in the OLR would produce an increase in the sludge production rate. Nonetheless, this relation is inversed and it can be attributed to inhibition's effects on the bacteria due to higher concentrations of the substrate in the influent. Generally speaking, at high ORLs the COD removal efficiency is negatively affected because it reduces microbial activity, and VFAs may accumulate deteriorating the system's performance [K. Wong, et. al. 2009, J. Bohdziewicz, et. al. 2008, K.C. Wijekoon, et. al. 2011].

On the other hand, higher SRTs are expected to produce less sludge due to the presence of more old bacteria with a lower growth rate. Moreover, these bacteria occupy the interstices between new bacteria, preventing easy access to nutrients and substrate.

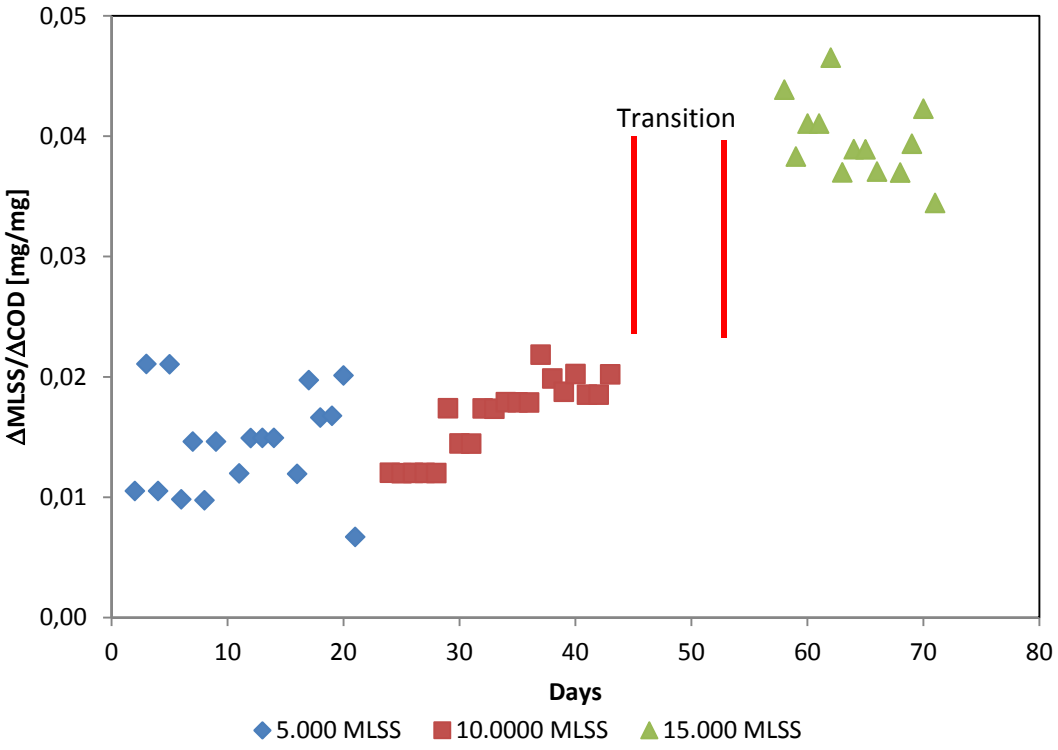

Figure 7.16 Sludge production throughout the experiment

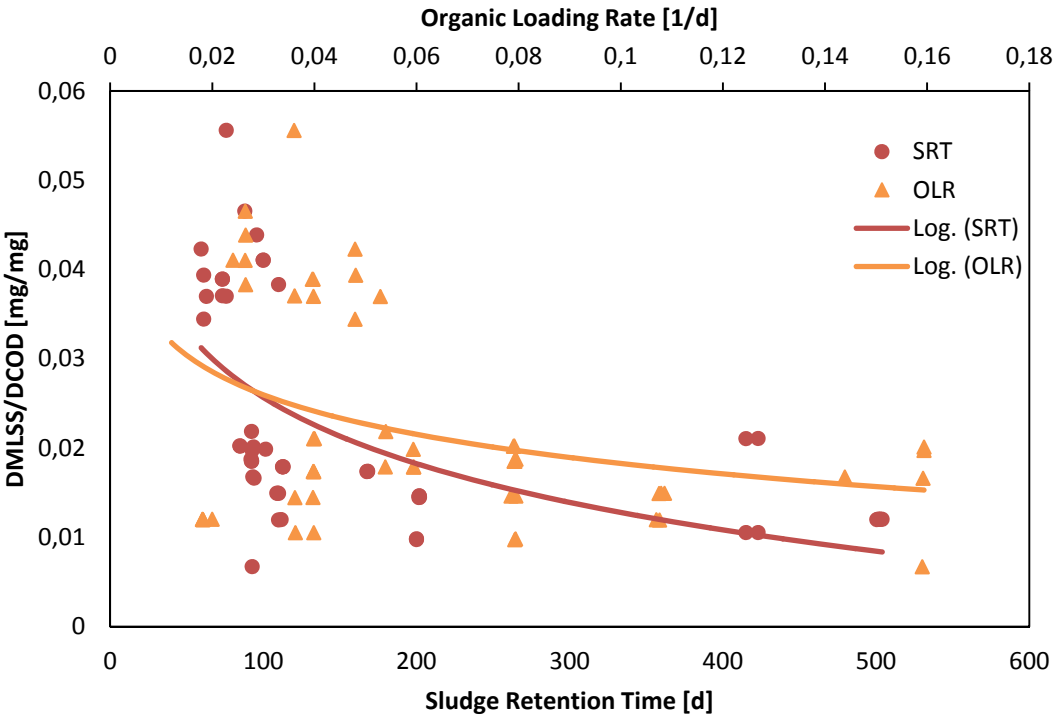

Figure 7.17 Effect of OLR and SRT on sludge production throughout the experiment.

7.1.3 Phosphate removal performance

Another analysis to check the performance of the system and membrane is the phosphate removal. During the whole experiment phosphate was monitored in the permeate and the bioreactor itself to calculate the removal efficiency of the membrane.

At 10,000 mg/l of MLSS the removal was around 70-80% as shown in Figure 7.18. During the different phases of COD concentrations the maximum removals were 77.5%, 72.2%, 75.7% and 86.1% at 2000, 4000, 6000 and 8000 ppm COD, respectively. Therefore, it can be stated that the removal was quite stable at this stage.

During the 15,000 mg/l MLSS concentration the phosphate removal presented a variation between the beginning and the end of the stage as it can be inferred from Figure 7.18. During this stage phosphate removal efficiency has shown an increment from 52% at 2000 ppm COD up to 84% at 8000 ppm COD. During the first two phases (2000 ppm and 4000 ppm COD) the removal presented this trend to increase, whereas in the last two phases (6000 ppm and 8000 ppm COD) the removal stabilized around 80%, varying from 77% to 84%, as shown in Figure 7.18.

Phosphate removal efficiency presented constant values at 5,000 mg/l of MLSS concentration as it can be seen in Figure 7.18, around 80%. During the first three phases of COD concentrations, i.e. 2000 ppm, 4000 ppm and 6000 ppm, the removal efficiency varied within a narrow range from 78.4% to 85.5%, presenting high values above 78% during every phase. At 8000 ppm COD concentration phosphate removal efficiency dropped to 77% and stayed stable as shown in Figure 7.18.

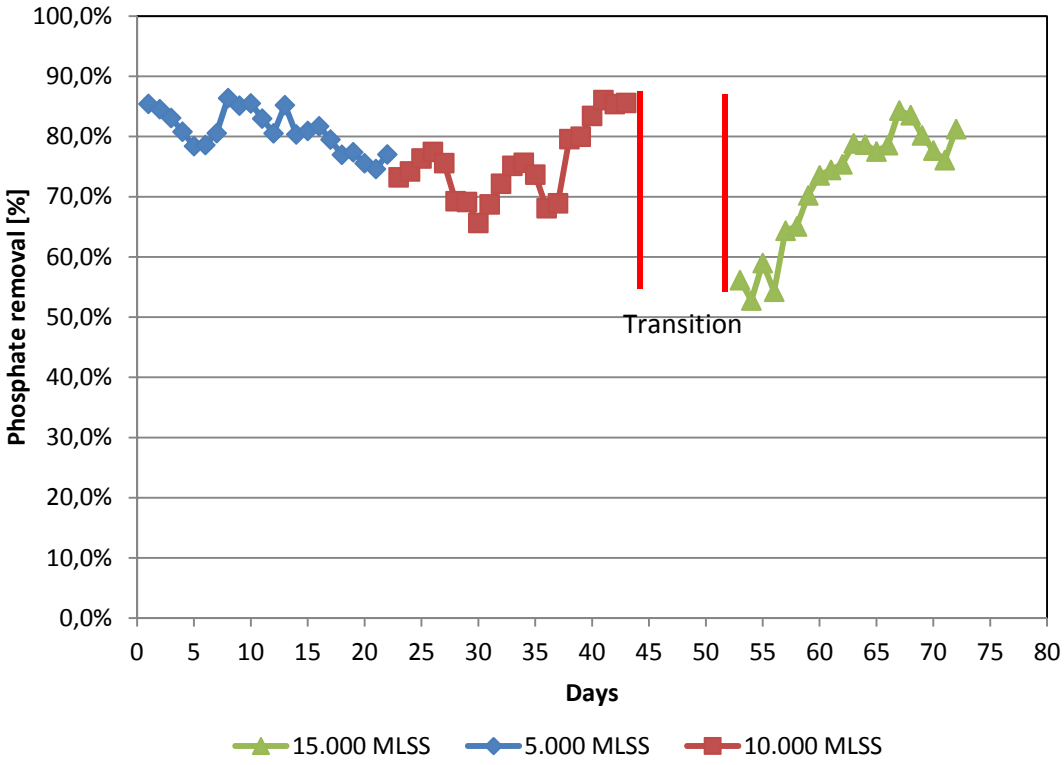

Figure 7.18 Phosphate removal efficiencies at 5,000, 10,000 and 15,000 mg/l MLSS

7.2 DETERMINATION OF BIOKINETIC COEFFICIENTS

7.2.1 Kinetic model equation

The basic equations describing microorganisms' growth and growth-limiting substrate utilization in the anaerobic community are based on the Monod (1949) equations [Udo Wiesmann], nonetheless several other authors (Teissier, Contois and Moser) have proposed other expressions [Metcalf & Eddy, et. al. 1991]. Monod's model is still nowadays one of the most widely used for the study of anaerobic biokinetic coefficients [Metcalf & Eddy, et. al. 1991; J. Beltran, et. al. 2008; Mirzaman Zamanzadeh, et. al. 2013; Anwar Ahmad, et. al. 2014]. This model was accepted by the IAWPRC task group [M. Henze et. al. 1987] as the fundamental basis for the microorganisms' growth.

Microorganisms require substrate for three main functions:

- To synthetize new cell material,
- To synthetize extra-cellular products, and
- To provide sufficient energy to drive the synthetic reaction and maintain concentrations of materials within the cell which are different from those in the environment.

In both batch and continuous culture systems the rate of growth of bacterial cells can be defined by the following relationship:

$$r_s = \mu X \tag{7.1}$$

Where r_s = rate of bacterial growth, mass/unit volume.time

μ = specific growth rate, 1/time

X = concentration of microorganisms, mass/unit volume

Because dX/dt = r_s for the batch culture, the following relationship is also valid for a batch reactor:

$$\frac{dX}{dt} = \mu X \tag{7.2}$$

The effect of a limiting substrate or nutrient can often be defined adequately using the following expression proposed by Monod (1949):

$$\mu = \mu_m \frac{S}{k_s + S} \tag{7.3}$$

Where μ_m = maximum specific growth rate, 1/time

S = concentration of growth limiting substrate surrounding the biomass, mass/unit volume

k_s = saturation constant which is numerically equal to the substrate concentration at $\mu = 0.5\mu_m$, mass/unit volume

Substituting the value of μ from Equation 7.3 in Equation 7.1, the resulting expression for the rate of growth is:

$$r_g = \frac{\mu_m XS}{k_s + S} \tag{7.4}$$

In batch and continuous growth culture systems, a portion of the substrate is converted to new cells and other portion is oxidized to inorganic and organic end-products. The relationship between the mass of bacteria produced and the mass of organic substrate removed is quantified by the yield coefficient Y, which is expressed as:

$$Y = \frac{dX/dt}{dS/dt} \tag{7.5}$$

The yield coefficient is usually assumed for a given biological process treating a specific waste, and it also depends upon:

- Various physical parameters of cultivation,
- Substrate polymerization degree,
- Metabolism pathways,
- Growth rate, and
- Oxidation state of the carbon source and nutrient elements.

The relationship between the rate of substrate utilization and the growth rate is as follows:

$$r_s = -Yr_{su} \tag{7.6}$$

Where r_{su} is the substrate utilization rate, mass/unit volume.time

In bacterial systems, used for wastewater treatment, the distribution of cell ages is such that not all cells in the system are in the log-growth phase. Consequently, the expression for the growth rate must be corrected to account for the energy required for cell maintenance. Other factors such as death and predation must also be considered. Usually these factors are lumped together and it is assumed that the decrease in cell mass caused by them is proportional to the concentration of organisms present. This decrease is known as endogenous decay, r_d, and it can be expressed as:

$$r_d = -Xk_d \tag{7.7}$$

Where r_d = endogenous decay, mass/unit volume.time

k_d = endogenous decay coefficient, 1/time

The biomass growth in the process can be expressed then as:

$$\frac{dX}{dt} = \mu X - Xk_d \tag{7.8}$$

Combining Equations 7.1 and 7.5 gives:

$$\frac{dS}{dt} = \mu \frac{X}{Y} \tag{7.9}$$

Rearranging Equation 7.9 and substituting in Equation 7.8:

$$\frac{dX}{dt} = Y\frac{dS}{dt} - Xk_d \tag{7.10}$$

Rearranging Equation 7.10:

$$\mu = UY - k_d \tag{7.11}$$

Where U is the specific substrate utilization rate, 1/time, and is represented by:

$$U = \frac{Q(S_0 - S)}{VX} \tag{7.12}$$

Where Q = flow rate, volume/time

S_0 = influent substrate concentration, mass/unit volume

S = effluent substrate concentration, mass/unit volume

When combining equations 7.1 to 7.12 it is formed the basis of the mathematical model for the submerged anaerobic membrane bioreactor process (SAnMBR).

Figure 7.19 shows the schematic diagram for the SAnMBR. The model is made with the following assumptions:

- The reactor is completely mixed (mixed was provided by mechanical mixing with a mixer)
- The volume of the reactor is constant (the inflow is equal to the permeate flow) this was achieved by using a mechanical float
- Complete rejection of MLSS (no biomass is allowed to go out with the permeate)
- Substrate is not rejected
- No microbial solids are contained in the influent substrate

The rate equations describing the performance of the system are the mass balance equations of both the biomass and substrate. These can be expressed as follows:

Biomass balance:

$$\begin{bmatrix} Rate\ of\ change \\ of\ biomass\ in \\ the\ reactor \end{bmatrix} = \begin{bmatrix} Rate\ of\ increase \\ due\ to\ growth \end{bmatrix} - \begin{bmatrix} Rate\ of\ loss\ due\ to \\ endogenous\ decay \end{bmatrix} - \begin{bmatrix} Deliberate \\ wastage \end{bmatrix}$$

The mathematical representation of the above statement is:

$$V\frac{dX}{dt} = \mu XV - k_d XV - Q_w X \tag{7.13}$$

Where V = reactor volume, L

X = biomass concentration in the reactor, mg/l

μ = specific growth rate, 1/day

Q_w = wastage flow rate, l/day

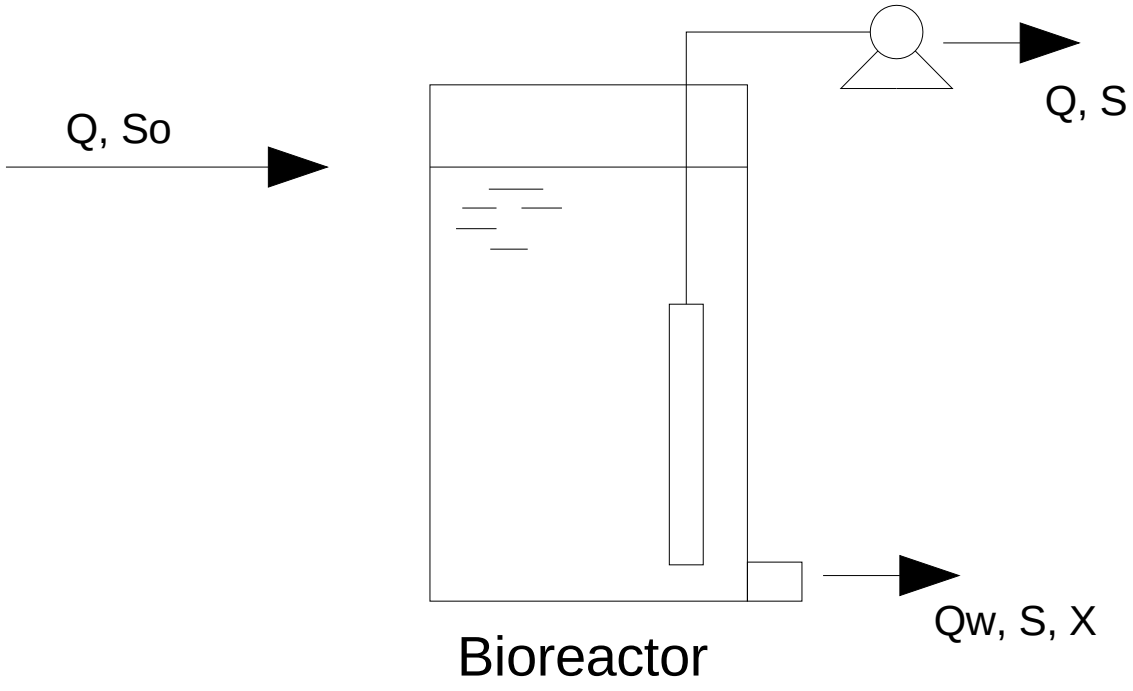

Figure 7.19 SAnMBR (completely mixed)

For steady state conditions, dX/dt = 0, therefore Equation 7.13 can be rewritten as follows:

$$\mu = k_d + \frac{Q_w}{V} \tag{7.14}$$

As the sludge retention time (SRT) is defined as:

$$SRT = \frac{Total\ mass\ of\ organisms\ in\ the\ reactor}{Total\ mass\ of\ organisms\ leaving\ the\ system\ per\ day}$$

It can be written:

$$SRT = \frac{VX}{Q_w X} = \frac{V}{Q_w} \tag{7.15}$$

Rearranging and substituting Equation 7.15 into 7.14, the following expression is obtained:

$$\mu = k_d + \frac{1}{SRT} \tag{7.16}$$

Substituting Equation 7.3 in 7.16 it can be obtained the steady state for substrate concentration in the reactor:

$$S = \frac{K_s\left(\frac{1}{SRT} + k_d\right)}{\mu_m - \left(\frac{1}{SRT} + k_d\right)} \tag{7.17}$$

Substrate balance:

$$\begin{bmatrix} Rate\ of \\ change \\ of\ substrate \\ in \\ the\ reactor \end{bmatrix} = \begin{bmatrix} Rate\ of \\ input \\ of\ the \\ feed \\ substrate \end{bmatrix} - \begin{bmatrix} Removal \\ rate \\ due\ to \\ biomass \\ utilization \end{bmatrix} - \begin{bmatrix} Removal\ rate \\ due\ to \\ washout \end{bmatrix} - \begin{bmatrix} Substrate \\ loss \\ during \\ deliberate \\ wastage\ of \\ biomass \end{bmatrix}$$

The mathematical representation of the above mentioned could be written as:

$$V\frac{dS}{dt} = QS_0 - \mu\frac{XV}{Y} - S(Q - Q_w) - Q_wS \tag{7.18}$$

If steady state prevails, then dS/dt = 0 and Equation 7.18 can be rewritten as:

$$\frac{Q}{V}(S_0 - S) = \mu\frac{X}{Y} \tag{7.19}$$

Substituting Equation 7.16 into 7.19 gives the biomass concentration at steady state conditions:

$$X = Y\frac{Q(S_0 - S)}{k_d + \frac{1}{SRT}} \tag{7.20}$$

7.2.2 Determination of kinetic coefficients

The purpose of this study was to gather data about the rate of cell growth and substrate consumption. This enables to calculate the required reactor volume to scale up the process. The kinetic coefficients of a biological system have been generally determined experimentally using complete-mixed continuous flow or batch lab-scale reactors.

In a complete-mixed continuous flow reactor the determination of the kinetic coefficients is mainly achieved by gathering data from lab-scale or pilot plant experiments, operating the system at different HRTs or SRTs, and allowing a steady state condition to be attained with each combination. Therefore, accurate measurements of the biomass and permeate substrate concentrations are written down. The kinetic coefficients namely k_s, μ, Y and k_d can be determined through the

linearization of Equations 7.17 and 7.20, giving equation 7.21 for the determination of k_d and Y, and equation 7.22 for μ_m and K_s:

$$\frac{Q}{VX}(S_0 - S) = \frac{1}{Y}\frac{1}{SRT} + \frac{k_d}{Y} \tag{7.21}$$

$$\frac{SRT}{1 + SRTk_d} = \frac{K_s}{\mu_m}\frac{1}{S} + \frac{1}{\mu_m} \tag{7.22}$$

Plotting $\frac{Q}{VX}(S_0 - S)$ vs $\frac{1}{SRT}$ from Equation 7.21 the slope and the Y axis interception will determine the kinetic coefficients Y and k_d, respectively. Substituting the obtained value of k_d into Equation 7.22 and then plotting $\frac{SRT}{1+SRTk_d}$ vs $\frac{1}{S}$, the slope and the Y axis interception will determine the remaining kinetic coefficients K_s and μ_m, respectively.

The studies of the kinetic coefficients for the SAnMBR were performed as stated hereinbefore, but as it was a steady flux with no HRT variations, SRT was used instead. The latter could be targeted by running the system at different OLR's and wasting different volumes of biomass from the system as they grew to control the MLSS at a fixed value.

In order to maintain the MLSS concentration within a narrow range when studying the kinetic coefficients at different concentrations, biomass was measured and wasted on daily basis, thus attaining the required concentration. Due to the fact that it is an anaerobic media the growth was expected to be slow, therefore high care was taken in order not to waste more than enough. Thus, values varied within a range close to the desired concentration. The steady state condition was assumed to be reached when the

sludge growth and the permeate COD were almost constant with no noticeable fluctuations.

The kinetic study was started with a 10,000 mg/l MLSS concentration, and due to the fact that the media had been already acclimatized for two months to the synthetic dairy wastewater at low COD concentration (2000 ppm), that the bioreactor had been running for the previous 30 days and that the first concentration of COD was 2000 ppm, the first point of the steady state condition was successfully achieved. At these conditions (2000 ppm COD) the steady state was kept for 3 days with 0,3% variation, following the increase of COD concentration to 4000 ppm, then 6000 ppm and finally to 8000 ppm, creating four points in total. Before moving to the next COD concentration a steady state condition was assured to be achieved for 3 or 4 days, with a modest variation of less than 5%. When different OLRs were tried for one stage, the next stage of MLSS concentration was started, and the procedure was repeated.

Maximum COD removal efficiencies achieved for the ORLs of 2000 ppm, 4000 ppm, 6000 ppm and 8000 ppm were 83.4%, 86.5%, 83.9 and 74.2% at 10,000 mg/l MLSS, respectively, and 88.4%, 91.4%, 90% and 79.8% at 15,000 mg/l MLSS, respectively. At 5,000 mg/l MLSS the maximum COD removal efficiencies were 47.5%, 51.3%, 55.8% and 37.3% for the same OLRs, respectively. As observed, the maximum COD removal efficiency at both 10,000 mg/l and 15,000 mg/l MLSS was achieved at the second phase of 4000 ppm COD, and at 5,000 mg/l was achieved at the third phase of 6000 ppm COD. Interestingly, when the COD concentration was 6000 ppm at 10,000 mg/l MLSS, the removal efficiency dropped 3 points of percentage whereas at 15,000 mg/l MLSS this efficiency was practically stable. With a further increase to 8000 ppm

of COD it abruptly dropped to 37.3%, 74% and 79.8% at 5,000 mg/l, 10,000 mg/l and 15,000 mg/l MLSS, respectively. This indicates that bacteria are not able to break down the same percentage of COD fed to them as with previous concentrations tried and that this bacteria could not cope with this OLR.

In Table 7.1, Table 7.2 and Table 7.3 it is shown the steady state data for 5,000 mg/l, 10,000 mg/l and 15,000 mg/l of MLSS concentration, respectively. Following the Monod equations previously discussed, linear regression was applied making use of Equations 7.21 and 7.22 plotted in Figure 7.20 and Figure 7.21, respectively for the MLSS concentration of 5,000 mg/l. For the MLSS concentration of 10,000 mg/l the plots are shown in Figure 7.22 and Figure 7.23, and for 15,000 mg/l in Figure 7.24 and Figure 7.25, in the same order as before.

The kinetic coefficients gathered from these graphs are shown in Table 7.4 at 5,000 mg/l, 10,000 mg/l and 15,000 mg/l of MLSS. Table 7.5 shows a comparison of the kinetic coefficients obtained in different experiments treating different types of wastewater in aerobic and anaerobic conditions. Ranges of the anaerobic kinetic coefficients presented in the literature and compared with the results of this experiment are presented in Table 7.6. Perusal of the literature showed that Monod's equations can be successfully applied to anaerobic systems [Metcalf & Eddy, et. al. 1991; J. Beltran, et. al. 2008; Mirzaman Zamanzadeh, et. al. 2013; Anwar Ahmad, et. al. 2014].

Steady-state period	Q	X	S0	S	SRT	Q(S0-S)/VX	1/SRT	1/S	SRT/ (1+SRT*k_d)
day	l/d	mg/l	mg/l	mg/l	d	1/d	1/d	l/mg	d
1-5	2,12	5006	2000	1050	420	0,0183	0,0024	0,000952	220,17
6-10	2,16	5034	4000	1949	201	0,0400	0,0050	0,000513	140,14
11-16	2	5035	6000	2652	109	0,0604	0,0091	0,000377	88,50
17-21	2,16	5006	8000	5018	93	0,0585	0,0107	0,000199	77,58

Table 7.1 Steady state data at 5.000 mg/l MLSS

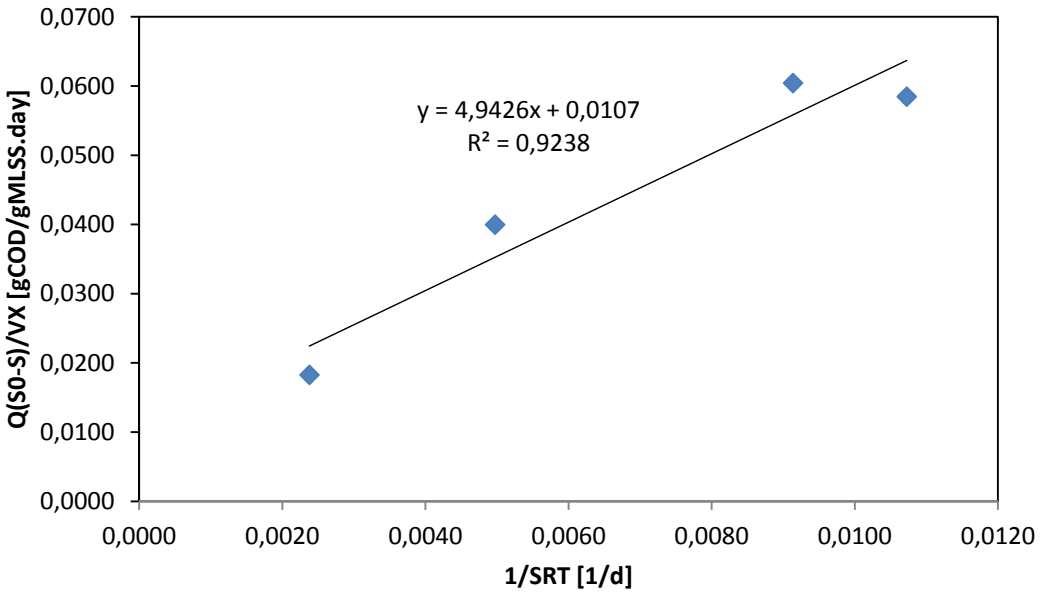

Figure 7.20 Determination of Y and k_d values for 5,000 mg/l MLSS

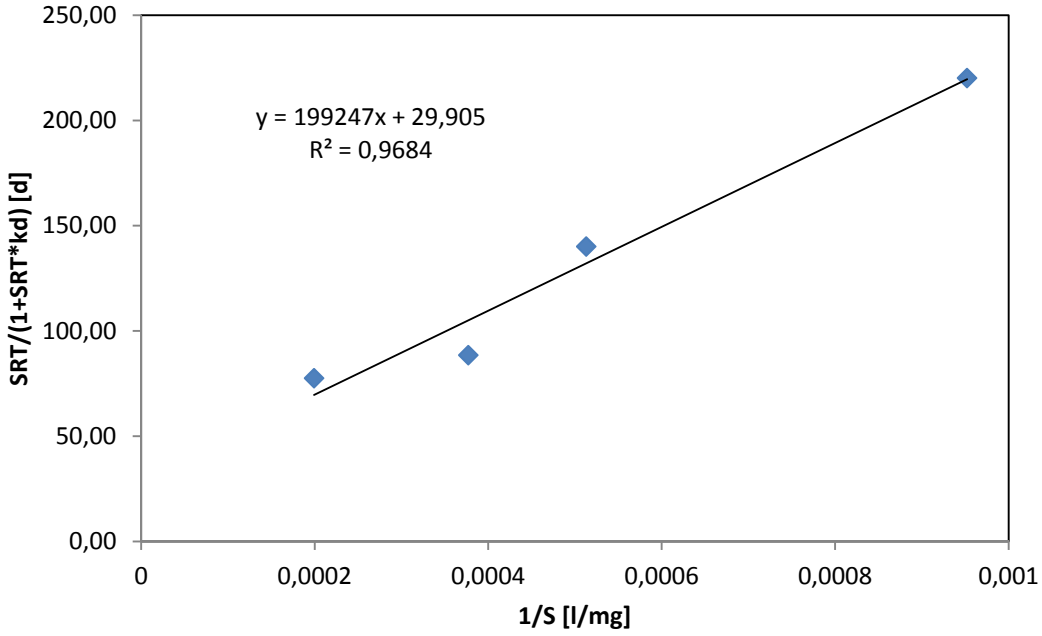

Figure 7.21 Determination of μ_m and K_s values for 5,000 mg/l MLSS

Steady-state period	Q	X	S0	S	SRT	Q(S0-S)/VX	1/SRT	1/S	SRT/ (1+SRT*k_d)
day	l/d	mg/l	mg/l	mg/l	d	1/d	1/d	l/mg	d
23-28	2,04	10014	2000	336	502	0,0154	0,0020	0,002980	295,32
29-33	2,12	10034	4000	545	185	0,0332	0,0054	0,001834	147,02
34-38	2,12	10048	6000	965	113	0,0483	0,0089	0,001036	97,48
39-44	2,2	10045	8000	2064	90	0,0591	0,0111	0,000485	79,75

Table 7.2 Steady state data at 10.000 mg/l MLSS

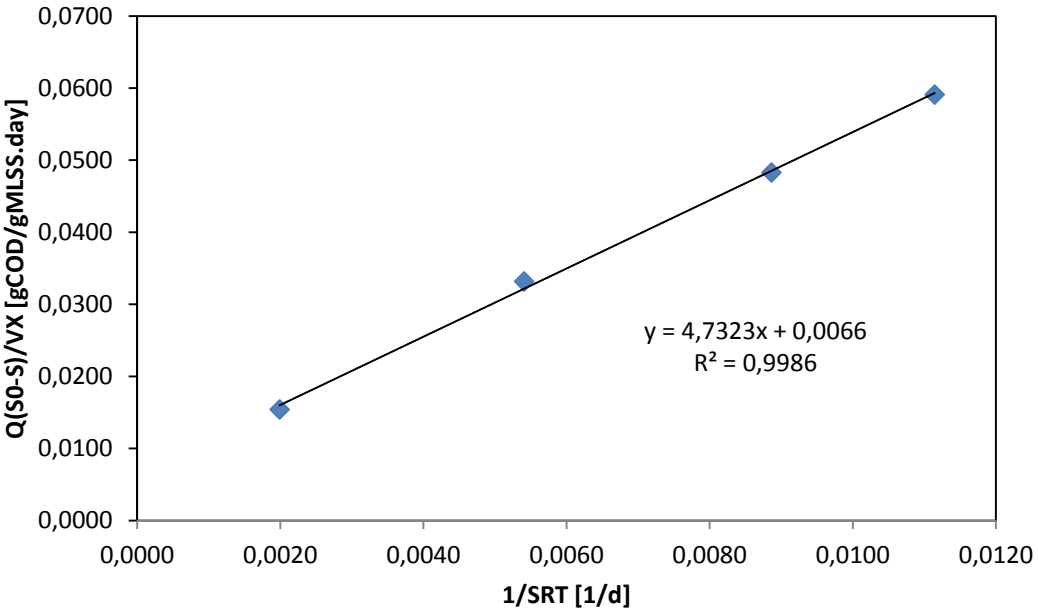

Figure 7.22: Determination of Y and k_d values for 10,000 mg/l MLSS.

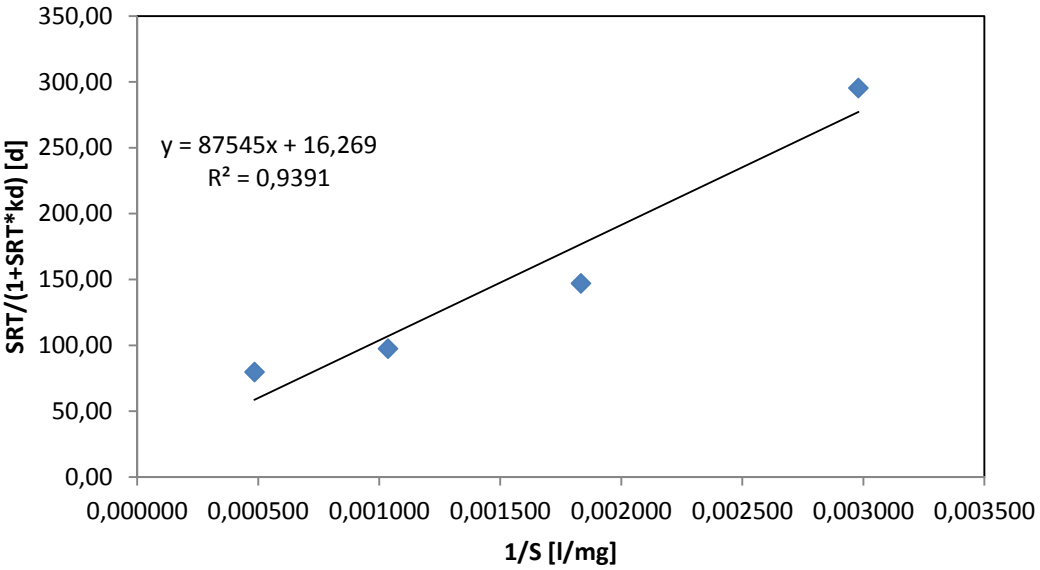

Figure 7.23: Determination of μ_m and K_s values for 10,000 mg/l MLSS

Steady-state period	Q	X	S0	S	SRT	Q(S0-S)/VX	1/SRT	1/S	SRT/ (1+SRT*k_d)
day	l/d	mg/l	mg/l	mg/l	d	1/d	1/d	l/mg	d
53-57	2,05	15027	2000	232	275	0,0110	0,0036	0,004310	218,54
58-62	2,2	15050	4000	346	99	0,0243	0,0101	0,002893	90,35
63-67	2,2	15000	6000	603	74	0,0360	0,0135	0,001658	69,34
68-72	2,05	15045	8000	1614	61	0,0396	0,0164	0,000620	57,82

Table 7.3 Steady state data at 15.000 mg/l MLSS

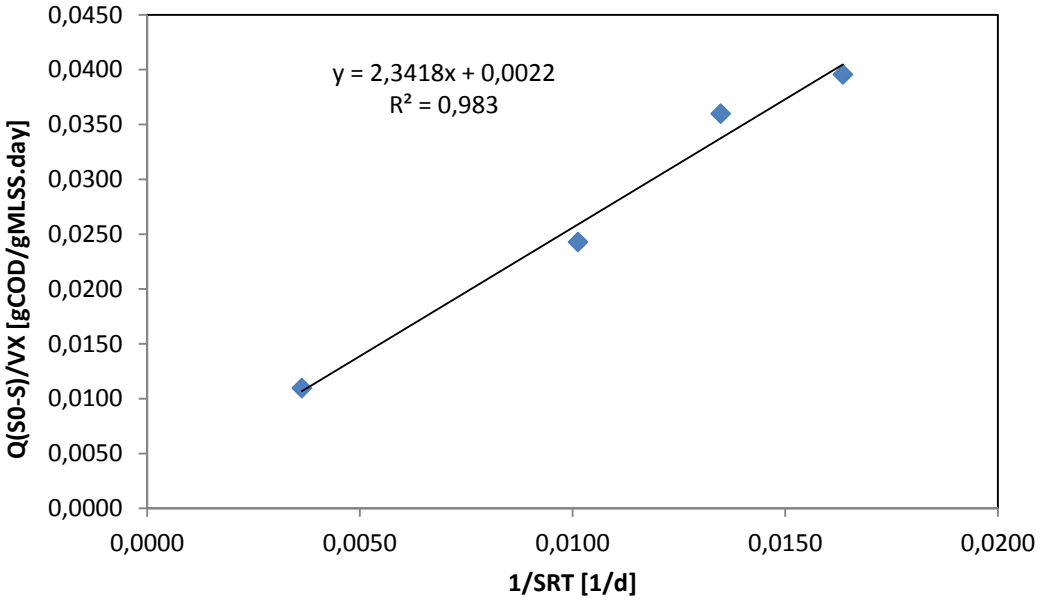

Figure 7.24 Determination of Y and k_d values for 15,000 mg/l MLSS

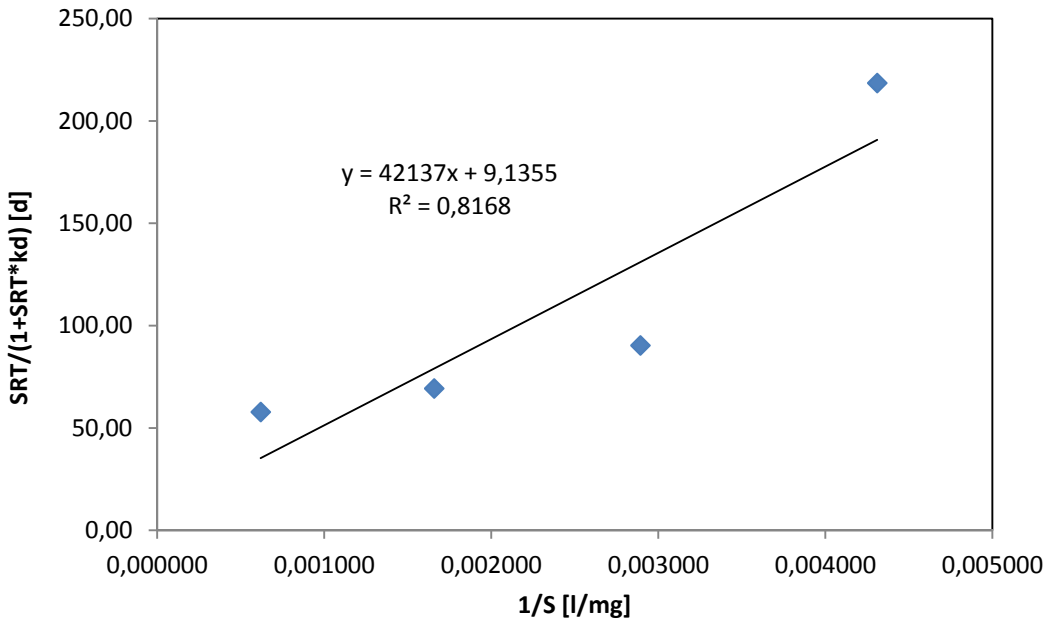

Figure 7.25 Determination of μ_m and K_s values for 15,000 mg/l MLSS

MLSS	Y (mg/mg)	K_d (d^{-1})	μ_m (d^{-1})	K_s (mg COD/l)
5000	0,2022	0,0022	0,0334	6663
10000	0,2113	0,0014	0,0615	5381
15000	0,4270	0,0009	0,1095	4612

Table 7.4 Biokinetic Coefficients for SAnMBR at different MLSS concentrations

	Substrate	Y (mg/mg)	K_d (d^{-1})	μ_m (d^{-1})	K_s (mg COD/l)	System	Reference
Photosynthesis bacteria	Dairy	0.2281	0.1383	1.69	174	MSBR	Jutamas et. al., 2010
	Coconut cream	0.1383	0.0008	0.32	8000	-	Kantawanichkul, 1990
	Domestic	0.36	ND	0.008	ND	MSBR	Somiya et. al., 1988
	Cassava starch	ND	ND	3.12	ND	-	Noparatnaraporn et. al., 1987, 1983
	Acetate	ND	0.014	ND	ND	-	Nakajima et. al., 1997
	Dairy	ND	ND	0.44	141	AS	Carta-Escobar et. al., 2005
	Dairy	0.153	0.022	ND	ND	UASB	Hwang and Hansen, 1992
	Dairy	0.29	0.14	9.9	134	Two-phase anaerobic	Yu et. al., 2002
	Dairy	0.2116	0.0131	0.7844	420.8	Anaerobic digestion	Hu et. al., 2002
	Glucose	0.31	1.56	64.8	2583	Anaerobic digestion	Udo Wiesmann et. al., 2007
	Acetate	0.027-0.057	0.0036-0.006	0.038-0.4	ND	Anaerobic digestion	Udo Wiesmann et. al., 2007
	Pesticide	0.148	0.05	3.37	4077	Anaerobic digestion	Chiu-Yue Lin, et. al. 1990

ND: Not Determined

Table 7.5 Biokinetic Coefficients for aerobic and anaerobic systems with different substrates

Substrate	Y (mg/mg)	K_d (d^{-1})	μ_m (d^{-1})	K_s (mg COD/l)	System
Dairy / Glucose	0.027 – 0.31	0.003 – 1.56	0.038 – 64.8	141 – 4077	Several
Dairy (This experiment)	0.2022 – 0.427	0.0009 – 0.0022	0.0334 – 0.1095	4612 – 6663	SAnMBR

Table 7.6 Biokinetic Coefficient's range comparison for anaerobic systems

From Table 7.4 it can be observed that kinetic coefficients varied at different MLSS concentrations, though for the 5,000 mg/l and 10,000 mg/l the yield coefficients (Y) are very close to each other, as the bacteria decay rates (k_d) are. The latter presented low values, meaning the decay of the bacteria was slow, and this is accompanied with the bacteria maximum growth yield (μ_m) which was not high either. This phenomenon was displayed in the experiment when the MLSS concentration presented a fairly low daily increase, giving higher SRTs. Thus, low bacteria growth rate and high k_s are correlated with low bacteria decay rate [Jutamas Kaewsuk, et. al. 2010]. In comparison with the values obtained in other studies shown in Table 7.5, Y, k_d and μ_m are within the range for dairy anaerobic treatment. The only value which is fairly high in every stage of the experiment is the half velocity constant, k_s, though is very close to values found in the literature. One trend that is well noticed while the MLSS concentration was increased, is that Y and μ_m increased whereas k_d and k_s decreased.

The value of k_s simply indicates the efficiency with which degradation occurs, thus if low substrate concentrations in the effluent are sought, low values of k_s are necessary [Michael D. LaGrega, et. al. 2001]. In this experiment, as shown in the Hydraulic Performance of the system before, values of the effluent substrate (COD) were high, therefore the values of the half-velocity constant are expected to be high. Lower values of k_s at higher MLSS implies a better performance of the system. Furthermore, this trend is accompanied by higher values of μ_m when increasing MLSS, which means the biomass growth is faster thus increasing the demand of substrate consumption, leading to lower effluent substrate, i.e. a better performance of the system, and therefore k_s decreases.

The variation of kinetic coefficients at different MLSS could be due to many reasons, starting with the fact that the experimental setup included a mixed culture and not an isolated type of bacteria for the given substrate utilized. Another could be the assumption of steady state conditions for the development of the Monod equations, which will bring a certain error when applying them to real conditions where several factors affect the efficiency of the process, even more in biological systems. Furthermore, the use of SRT instead of HRT in the equations and during the experiment to obtain the kinetic coefficients could bring differences. This is due to the fact that at different SRTs at a specific MLSS concentration certain types of bacteria could be fostered to grow faster than others (when talking about mixed cultures as in this investigation).

7.2.3 Simulation of steady state conditions and sensitivity analysis

To test the validity of the Monod's equations described hereinbefore in point 7.2.1, a simulation of equation 7.17 was performed and plotted in Figure 7.26. During the development of the final equations it was assumed that the SAnMBR was running under steady state conditions. Thus, equation 7.17 will predict the effluent COD for the different MLSS concentrations at different SRTs.

For this purpose the kinetic coefficient values shown in Table 7.4 were used and plugged into equation 7.17 to reproduce the simulated COD effluent values. This can be used for designing a pilot scale SAnMBR, which is the purpose of this kind of researches. The figure shows the trend that the bacteria follow, at a determined MLSS concentration, when varying SRT values. As it can be observed, the higher the SRT the lower the effluent COD till it reaches a point where for higher values of the SRT

the effluent COD is not affected anymore. For 10,000 mg/l and 15,000 mg/l of MLSS this point occurs after 300 days of SRT, whereas for the 5,000 mg/l MLSS it takes up to 550 days of SRT. This is because when increasing SRT bacteria will be fully grown and degrade the substrate at a maximum rate till a point where a further increase will accumulate old bacteria complicating the substrate easy access, limiting its removal. This can also happen because the system has reached the maximum COD removal that can be achieved. There is an irremovable COD portion in the influent.

In order to assess the influence of the biokinetic coefficients previously obtained on the effluent COD concentration, a sensitivity analysis was applied to the data. The values of k_d, k_s and μ_m where modified by ±50% individually, keeping the rest parameters constant. The analysis was ran by making use of equation 7.17 with the modified parameters in order to simulate the effluent COD concentrations as shown in Figure 7.27, Figure 7.28 and Figure 7.29 for the different MLSS concentrations.

In general, k_d and k_s are directly proportional to the simulated effluent COD, while μ_m is inversely proportional. The biokinetic parameter which produced more sensitiveness in the effluent COD, regardless of the MLSS concentration, was k_s as it can be inferred from all the figures. It was found that by increasing the MLSS concentration the effluent COD was less sensitive to all the parameters. Thus, it can be said that for higher MLSS concentrations the effluent COD is less sensitive to variations. Nevertheless, caution should be taken when working with μ_m due to the fact that small variations could bring out wrong results. This last affirmation could be confirmed when modifying μ_m by -50%, the effluent COD varied greatly with no pattern followed, thus the reason for not having included those results in the graphs.

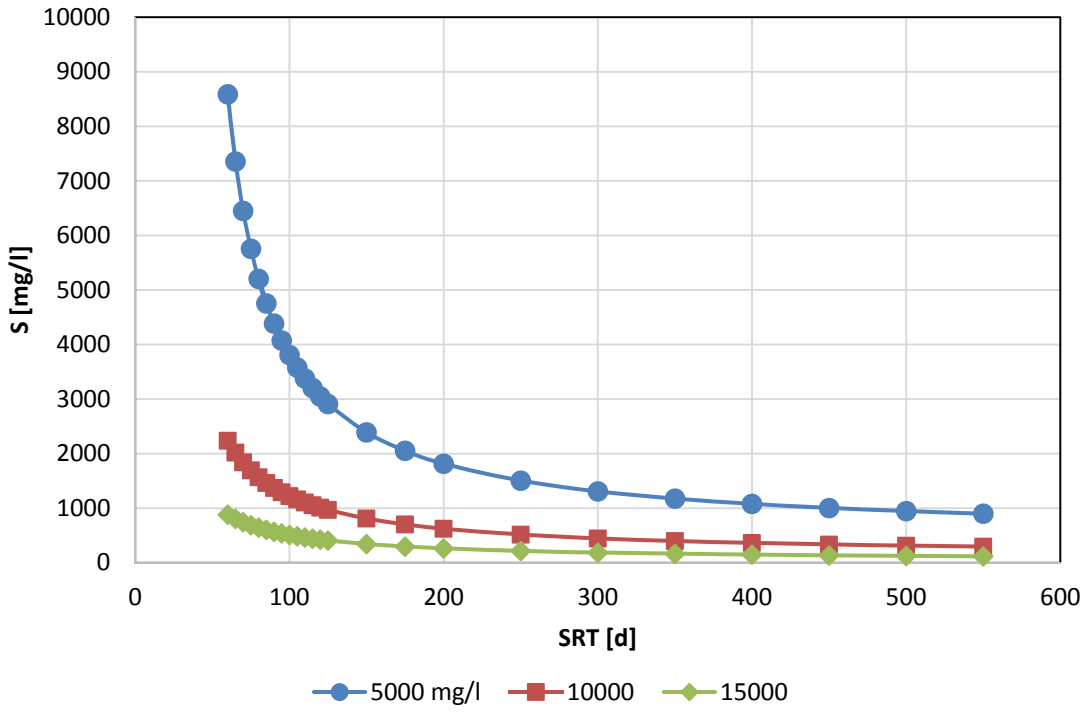

Figure 7.26 Comparison of simulated effluent COD at different MLSS concentrations

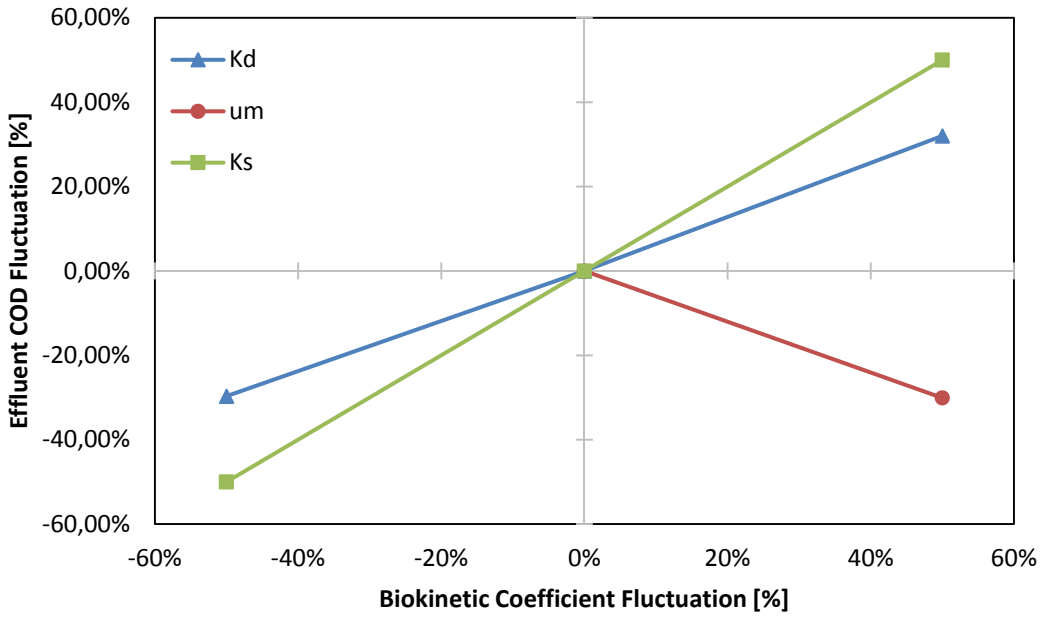

Figure 7.27 Sensitivity analysis of biokinetic coefficients at 5,000 mg/l MLSS.

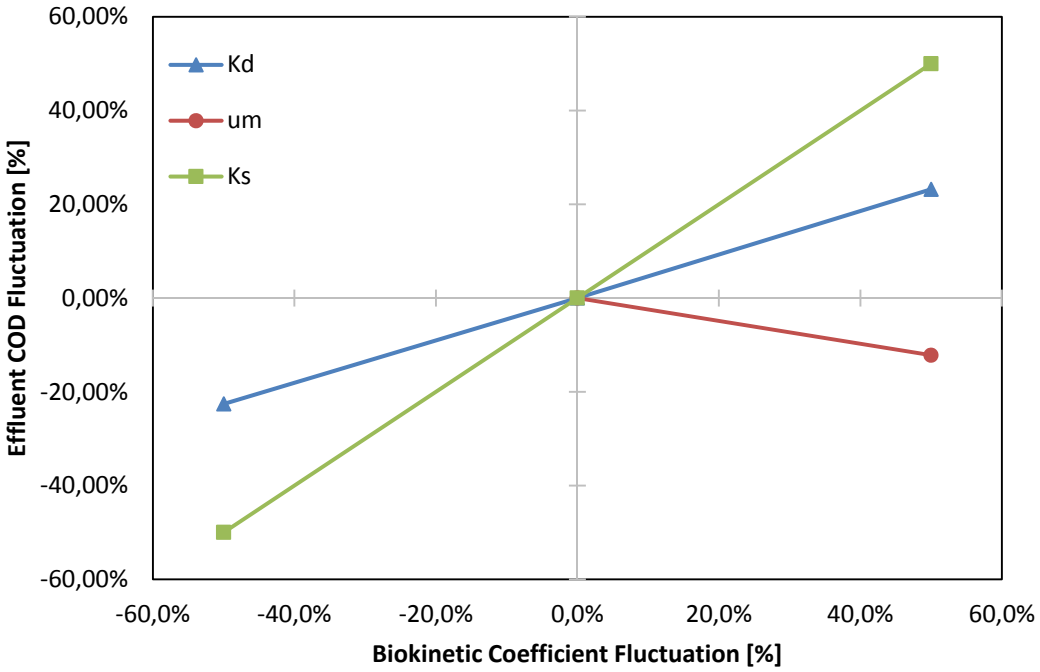

Figure 7.28 Sensitivity analysis of biokinetic coefficients at 10,000 mg/l MLSS.

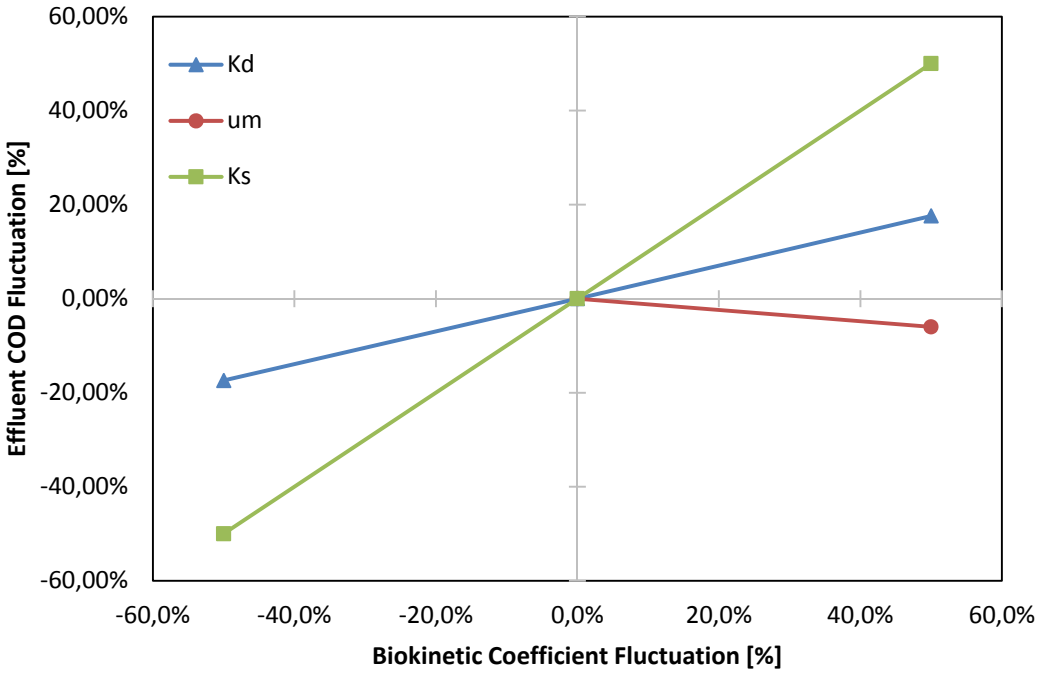

Figure 7.29 Sensitivity analysis of biokinetic coefficients at 15,000 mg/l MLSS.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 GENERAL CONCLUSIONS

- Further understanding of SAnMBR for dairy wastewater treatment was achieved running the experiment at different operating conditions of OLR, MLSS and SRT. COD removal efficiency improved with increasing MLSS concentration, ranging in this research from 55% to over 91%.
- At a MLSS concentration of 10,000 mg/l, the kinetic coefficients were: Y = 0.2113 mg/mg, k_d = 0.0014 d^{-1}, μ_m = 0.0615 d^{-1} and k_s = 5381 mg COD/l. At an OLR of 4000 ppm the maximum COD removal efficiency was achieved, reaching to 86.4%. At an OLR of 2000 ppm the maximum biogas yield was obtained, with a value of 0.17 l/gr COD_r. Total gas obtained in this stage was 30.3 l.
- At a MLSS concentration of 15,000 mg/l, the kinetic coefficients were: Y = 0.427 mg/mg, k_d = 0.0009 d^{-1}, μ_m = 0.1095 d^{-1} and k_s = 4612 mg COD/l. At an OLR of 4000 ppm the maximum COD removal efficiency was achieved, reaching to 91.4%. At OLRs of 4000 and 6000 ppm the maximum biogas yield was obtained, with a value of 0.18 l/gr COD_r. Total gas obtained in this stage was 35.56 l.

- At a MLSS concentration of 5000 mg/l, the kinetic coefficients were: Y = 0.2022 mg/mg, $k_d = 0.0022\ d^{-1}$, $\mu_m = 0.0334\ d^{-1}$ and $k_s = 6663$ mg COD/l. At an OLR of 6000 ppm the maximum COD removal efficiency was achieved, reaching to 55.8%. At an OLR of 8000 ppm the maximum biogas yield was obtained, with a value of 0.104 l/gr COD_r. Total biogas obtained in this stage was 21.29 l.
- The value of pH in the system was kept constant within the optimum range for methanogenic bacteria (6.8 – 7.2) during all the stages and phases, though at the last phase on each stage (at 8000 ppm COD), the pH dropped to 6.7. All the values were within the range of pH interval of 6.5 to 8.5, with an optimum range from 6.8 to 7.5 for methanogenic bacteria. To successfully increase the pH and keep it within these values, 2.5 N NaOH was utilized.
- Turbidity removal efficiency was over 98% at 10,000 and 15,000 mg/l of MLSS, and over 94% at 5,000 mg/l of MLSS.
- The system showed good performance treating synthetized dairy wastewater at different OLR and MLSS concentrations.
- Monod's equations were used to obtain the kinetic coefficients. The simulation study showed to be in accordance to the experimental data. With the kinetic coefficients it is possible to design a pilot scale wastewater treatment plant.

8.2 RECOMMENDATIONS

The following points are in need of further research:

- The load shock that the system can withstand to.
- The ability of the system to treat other inorganic and organic chemicals should be tested for toxic loading tests.
- Chemical inhibitors levels, as well as the maximum concentration of those inhibiting chemicals at which the system can still acclimatize.
- Ways of improving biogas production. By doing this the economical side of the SAnMBR system could be improved. Also it would bring a better idea of the amount of energy produced in KW/hr.
- Water hammer produced by an automated valve to control MF or UF membrane fouling, as there is only one study on this issue with promising results, overcoming backwashing methodology. This methodology was scheduled to be applied to the research but it could not due to technical-expertise issues.
- Energy aspects of SAnMBR operations. Not much information is available in what respects to the energy intake as a bulk or by each of its components, and the optimization of this intake.

APPENDIX A

Raw data for Biokinetic studies

Day	Influent COD [mg/l]	Effluent COD [mg/l]	Flux	MLSS		SRT [d]
			[l/m^{2}hr]	Before wasting	After wasting	
1	2000	1050	2.08	5120	5010	-
2	2000	1050	2.08	5020	5010	415.1
3	2000	1051	2.29	5010	4990	423.1
4	2000	1050	2.29	5020	5010	423.1
5	2000	1050	2.29	5030	5010	415.1
6	4000	1965	2.29	5050	5030	200.0
7	4000	1950	2.29	5050	5020	201.8
8	4000	1948	2.29	5060	5040	200.0
9	4000	1949	2.29	5110	5080	201.8
10	4000	1949	2.08	5160	5000	201.8
11	6000	2661	2.08	5120	5080	111.7
12	6000	2650	2.08	5100	5050	110.0
13	6000	2653	2.08	5080	5030	109.5
14	6000	2652	2.08	5050	5000	108.9
15	6000	2652	2.08	5110	5000	111.1
16	6000	2652	2.08	5090	5050	110.0
17	8000	4960	2.29	5050	4990	92.8
18	8000	4993	2.29	5050	5000	94.0
19	8000	5019	2.08	5080	5030	93.2
20	8000	5018	2.29	5050	4990	93.6
21	8000	5018	2.29	5040	5020	92.8
22	8000	5018	2.29	5060		91.7

Raw data for Biokinetic studies at 5,000 mg/l of MLSS

Day	Influent COD [mg/l]	Effluent COD [mg/l]	Flux	MLSS		SRT [d]
			[l/m^{2}hr]	Before wasting	After wasting	
23	2000	420	2.08	9980	9980	-
24	2000	339	2.29	10030	10010	501.5
25	2000	332	2.08	10010	9990	500.5
26	2000	336	2.08	10050	10030	502.5
27	2000	336	2.08	10080	10060	504.0
28	2000	335	2.08	10060	10040	503.0
29	4000	550	2.29	10080	10020	168.0
30	4000	545	2.29	10100	10050	202.0
31	4000	542	2.08	10080	10030	201.6
32	4000	547	2.29	10090	10030	168.2
33	4000	543	2.29	10060	10000	167.7
34	6000	971	2.08	10170	10080	113.0
35	6000	969	2.29	10140	10050	112.7
36	6000	965	2.29	10150	10060	112.8
37	6000	966	2.08	10160	10050	92.4
38	6000	965	2.29	10160	10060	101.6
39	8000	2137	2.29	10120	10010	92.0
40	8000	2071	2.29	10170	10050	84.7
41	8000	2064	2.29	10170	10060	92.5
42	8000	2064	2.29	10150	10040	92.3
43	8000	2063	2.29	10190	10070	84.9
44	8000	2063	2.29	10220	-	

Raw data for Biokinetic studies at 10,000 mg/l of MLSS

Day	Influent COD [mg/l]	Effluent COD [mg/l]	Flux	MLSS		SRT [d]
			[l/m^{2}hr]	Before wasting	After wasting	
53	2000	246	2.29	15050	15050	-
54	2000	231	2.08	15160	15010	220.0
55	2000	233	2.08	15120	14990	275.0
56	2000	232	2.08	15130	15040	275.0
57	2000	232	2.08	15170	15050	275.0
58	4000	352	2.29	15160	15000	95.7
59	4000	345	2.29	15160	15020	110.0
60	4000	345	2.29	15220	15070	100.0
61	4000	346	2.08	15200	15050	100.0
62	4000	346	2.29	15200	15030	88.0
63	6000	594	2.29	15170	14970	75.9
64	6000	604	2.29	15260	15050	73.3
65	6000	603	2.29	15200	14990	73.3
66	6000	603	2.08	15210	15010	73.3
67	6000	603	2.08	15300	15000	75.9
68	8000	1780	2.29	15240	15010	62.9
69	8000	1650	2.08	15250	15000	61.1
70	8000	1615	2.08	15300	15030	59.5
71	8000	1613	2.08	15280	15060	61.1
72	8000	1613	2.08	15310	-	

Raw data for Biokinetic studies at 15,000 mg/l of MLSS

Day	pH
1	6.96
2	6.89
3	6.90
4	6.95
5	6.98
6	6.86
7	6.70
8	7.07
9	6.88
10	7.00
11	7.25
12	7.00
13	6.87
14	6.76
15	6.79
16	6.87
17	6.89
18	6.85
19	6.82
20	6.65
21	6.77
22	6.85
23	6.99
24	6.93
25	6.9
26	6.8
27	6.85
28	6.85
29	6.81
30	6.84
31	6.85
32	6.6
33	6.79
34	6.93
35	6.89
36	6.86
37	6.85
38	6.86
39	6.73

Day	pH
41	6.74
42	6.74
43	6.66
44	6.73
45	7.11
46	7.11
47	7.07
48	7.08
49	7.11
50	7.08
51	7.11
52	7.11
53	6.81
54	6.93
55	7.08
56	7.11
57	7.06
58	7.07
59	7.22
60	6.98
61	7.01
62	7
63	7.05
64	6.72
65	6.93
66	6.77
67	6.97
68	6.95
69	7
70	6.85
71	6.53
72	6.77

APPENDIX B

Raw data for Bioreactor performance

Day	Gas			HRT	Phosphate [ppm]	Turbidity	Membrane Pressure
	L	Accum. [l]	[L/grCOD$_r$]	[d]	% removal	[NTU]	psi
1	0.35	0.35	0.09	11	85.5%	20.1	12.77
2	0.36	0.71	0.09	11	84.6%	80.5	13.26
3	0.40	1.11	0.09	10	83.1%	75.8	13.26
4	0.35	1.46	0.08	10	80.8%	70.1	13.26
5	0.38	1.84	0.09	10	78.4%	60	13.63
6	0.65	2.49	0.07	10	78.6%	50.1	13.26
7	0.60	3.09	0.07	10	80.6%	63.1	13.26
8	0.75	3.84	0.08	10	86.4%	44.6	13.26
9	0.72	4.56	0.08	10	85.2%	44.7	13.16
10	0.70	5.26	0.09	11	85.5%	40.5	12.96
11	1.10	6.36	0.09	11	83.0%	43.8	12.77
12	1.15	7.51	0.09	11	80.5%	42.2	13.16
13	1.11	8.62	0.09	11	85.2%	49.1	13.01
14	1.05	9.67	0.09	11	80.4%	41.8	12.77
15	1.08	10.75	0.09	11	81.0%	36.7	12.96
16	1.10	11.85	0.09	11	81.7%	41.4	13.16
17	1.50	13.35	0.09	10	79.5%	41.8	13.01
18	1.55	14.90	0.09	10	77.0%	41.0	12.77
19	1.60	16.50	0.10	11	77.4%	41.3	13.14
20	1.59	18.09	0.09	10	75.6%	50.1	12.77
21	1.60	19.69	0.09	10	74.6%	45.8	13.01
22	1.60	21.29	0.09	10	77.0%	31.3	12.96
23	0.78	0.78	0.11	11	73.1%	11.7	12.52
24	0.75	1.53	0.12	10	73.3%	25.4	12.52
25	0.74	2.26	0.18	11	74.2%	25.7	12.77
26	0.74	3.00	0.19	11	76.4%	19.5	12.52
27	0.69	3.69	0.17	11	77.5%	17	12.52
28	0.69	4.39	0.17	11	75.6%	23.5	12.52
29	1.20	5.59	0.17	10	69.3%	19.6	12.52
30	1.40	6.99	0.16	10	69.1%	18.3	12.52
31	1.20	8.19	0.15	11	65.7%	19.9	13.01
32	1.30	9.49	0.15	10	68.8%	25.6	13.01
33	1.30	10.79	0.15	10	72.2%	24.7	13.01
34	1.20	11.99	0.15	11	75.2%	25.5	12.77
35	1.98	13.97	0.15	10	75.7%	17.9	13.01
36	2.13	16.10	0.16	10	73.7%	22.8	12.77
37	1.82	17.91	0.15	11	68.1%	16.8	13.01
38	2.00	19.91	0.15	10	68.9%	19.5	12.77
39	1.85	21.76	0.15	10	79.6%	25	13.14

40	1.70	23.46	0.09	10	80.0%	18.9	12.77
41	1.75	25.21	0.10	10	83.4%	23.4	12.77
42	1.73	26.94	0.10	10	86.1%	24.1	12.52
43	1.65	28.59	0.09	10	85.4%	14.3	13.01
44	1.70	30.29	0.10	10	85.6%	13.9	13.01
53	0.80	0.80	0.13	10	56.2%	9.87	13.26
54	0.75	1.55	0.17	11	52.8%	8.77	13.14
55	0.70	2.25	0.18	11	59.0%	8.98	13.01
56	0.75	3.00	0.19	11	54.3%	9.05	13.26
57	0.70	3.70	0.18	11	64.4%	12.2	13.14
58	1.12	4.82	0.18	10	65.1%	12.5	12.77
59	1.55	6.37	0.17	10	70.2%	11.1	13.26
60	1.60	7.97	0.18	10	73.6%	11.2	13.01
61	1.53	9.50	0.19	11	74.5%	12.1	13.01
62	1.62	11.12	0.18	10	75.4%	11.3	13.01
63	2.03	13.15	0.15	10	78.9%	16.8	13.26
64	2.10	15.25	0.16	10	78.7%	16.1	13.51
65	2.12	17.37	0.16	10	77.5%	14.3	13.51
66	2.09	19.46	0.17	11	78.6%	18.7	13.26
67	2.05	21.51	0.17	11	84.3%	12.9	11.30
68	2.80	24.31	0.16	10	83.5%	24.6	13.14
69	3.00	27.31	0.16	11	80.2%	28.7	13.01
70	2.85	30.16	0.17	11	77.7%	24.8	13.26
71	2.70	32.86	0.17	11	76.1%	20.7	13.26
72	2.70	35.56	0.17	11	81.3%	22.5	12.77

NOMENCLATURE

MBR	Membrane Bioreactor
μ_m	Maximum specific growth rate [1/d]
AMBR	Aerobic Membrane Bioreactor
AnMBR	Anaerobic Membrane Bioreactor
BOD_5	Biological Oxygen Demand
COD	Chemical Oxygen Demand
COD_r	Chemical Oxygen Demand removed
FOG	Fat, Oil and Grease
GAC	Granulated Activated Carbon
HRT	Hydraulic Retention Time
k_d	Endogenous decay coefficient [1/d]
KFUPM	King Fahd University of Petroleum & Minerals
K_s	Half velocity constant [mg COD/l]
MF	Microfiltration
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
OC	Organic Carbon
OLR	Organic Loading Rate
PAC	Powder Activated Carbon
PES	Polyethersulfone
PVDF	Polyvinylidene difluoride
Q	Flow rate [l/d]
S	Effluent substrate concentration [mg/l]
S_0	Influent substrate concentration [mg/l]
SAnMBR	Submerged Anaerobic Membrane Bioreactor
SCOD	Soluble Chemical Oxygen Demand
SDW	Sinthetic Dairy Wastewater
SMBR	Submerged Membrane Bioreactor
SMP	Soluble Microbial Products

SRT	Sludge Retention Time	**TSS**	Total Suspended Solids
SS	Suspended Solids	**UF**	Ultrafiltration
TCOD	Total Chemical Oxygen Demand	**VFA**	Volatile Fatty Acids
		VS	Volatile Solids
TDS	Total Disolved Solids	**VSS**	Volatile Suspended Solids
TKN	Total Kjeldahl Nitrogen	**WHO**	World Health Organization
TMP	Transmembrane Pressure	**X**	Concentration of microorganisms [mg/l]
TN	Total Nitrogen		
TP	Total Phosphorous	**Y**	Growth yield coefficient [mg/mg]
TS	Total Solids		

REFERENCES

A. Akram (a), D.C. Stuckey, Biomass acclimatisation and adaptation during startup of a submerged anaerobic membrane bioreactor (SAMBR), Environ. Technol. 29 (2008) 1053–1065.

A. Akram (b), David C. Stuckey. Flux and performance improvement in a submerged anaerobic membrane bioreactor (SAMBR) using powdered activated carbon (PAC). Process Biochemistry 43 (2008) 93–102.

A. Asatekin, A.Menniti, S. Kang, M. Elimelech, E. Morgenroth, A.M.Mayes, Antifouling nanofiltration membranes for membrane bioreactors from self-assembling graft copolymers, J. Membr. Sci. 285 (2006) 81–89.

A. Beaubien, M. Baty, F. Jeannot, E. Francoeur, J. Manem, Design and operation of anaerobic membrane bioreactors: development of a filtration testing strategy, J. Membr. Sci. 109 (1996) 173–184.

A. Damayanti, Z. Ujang, M.R. Salim, The influenced of PAC, zeolite, and Moringa oleifera as biofouling reducer (BFR) on hybrid membrane bioreactor of palm oil mill effluent (POME), Bioresour. Technol. 102 (2011) 4341–4346.

A. Drews, Membrane fouling in membrane bioreactors—characterisation, contradictions, cause and cures, J. Membr. Sci. 363 (2010) 1–28.

A. Pierkiel, J. Lanting, Membrane-coupled anaerobic digestion of municipal sewage sludge, Water Sci. Technol. 52 (2005) 253–258.

A. Saddoud (a), I. Hassairi, S. Sayadi, Anaerobic membrane reactor with phase separation for the treatment of cheese whey, Bioresour. Technol. 98 (2007) 2102–2108.

A. Saddoud (b), M. Ellouze, A. Dhouib, S. Sayadi, Anaerobic membrane bioreactor treatment of domestic wastewater in Tunisia, Desalination 207 (2007) 205–215.

A. Saddoud (c), Ilem Hassari, Sami Sayadi. Anaerobic membrane reactor with phase separation for the treatment of cheese whey. Bioresource Technology, 2007, 98, 2102–2108.

A. Saddoud, M. Ellouze, A. Dhouib, S. Sayadi, A comparative study on the anaerobic membrane bioreactor performance during the treatment of domestic wastewaters of various origins, Environ. Technol. 27 (2006) 991–999.

A. Saddoud, S. Abdelkafi, S. Sayadi, Effects of domestic wastewater toxicity on anaerobic membrane-bioreactor (MBR) performances, Environ. Technol. 30 (2009) 1361–1369.

A. Santos, S. Judd, The commercial status of membrane bioreactors for municipal wastewater, Sep. Sci. Technol. 45 (2010) 850–857.

A. Santos, W. Ma, S.J. Judd, Membrane bioreactors: two decades of research and implementation, Desalination 273 (2011) 148–154.

A. Spagni, S. Casu, N.A. Crispino, R. Farina, D. Mattioli, Filterability in a submerged anaerobic membrane bioreactor, Desalination 250 (2010) 787–792.

A. Torres, A. Hemmelmann, C. Vergara, D. Jeison, Application of two-phase slug-flow regime to control flux reduction on anaerobic membrane bioreactors treating wastewaters with high suspended solids concentration, Sep. Purif. Technol. 79 (2011) 20–25.

A.P. Trzcinski, D.C. Stuckey, Treatment of municipal solid waste leachate using a submerged anaerobic membrane bioreactor at mesophilic and psychrophilic

temperatures: analysis of recalcitrants in the permeate using GC–MS, Water Res. 44 (2010) 671–680.

A.P. Trzcinski, D.C. Stuckey, Anaerobic digestion of the organic fraction of municipal solid waste in a two-stage membrane process, Water Sci. Technol. 60 (2009) 1965–1978.

A.Y. Hu, D.C. Stuckey, Treatment of dilute wastewaters using a novel submerged anaerobic membrane bioreactor, J. Environ. Eng. 132 (2006) 190–198.

Andreottola, G.; Foladori, P.; Ragazzi, M.; Villa, R. Dairy wastewater treatment in a moving bed biofilm reactor. Wat. Sci. Technol. 2002, 45 (12), 321-328.

Anwar Ahmad, Rumana Ghufran, Evaluation of the bio-kinetics of cement kiln dust in an upflow anaerobic sludge blanket reactor for treatment of palm oil mill effluent as a function of hydraulic retention time. Separation and Purification Technology 133 (2014) 129–137

B. Mahendran, H. Lin, B. Liao, S.N. Liss, Surface properties of biofouled membranes from a submerged anaerobic membrane bioreactor after cleaning, J. Environ. Eng. 137 (2011) 504–513.

B.E.L. Baeta, R.L. Ramos, D.R.S. Lima, S.F. Aquino, Use of submerged anaerobic membrane bioreactor (SAMBR) containing powdered activated carbon (PAC) for the treatment of textile effluents, Water Sci. Technol. 65 (2012) 1540–1547.

B.Q. Liao, J.T. Kraemer, D.M. Bagley, Anaerobic membrane bioreactors: applications and research directions, Crit. Rev. Environ. Sci. Technol. 36 (2006) 489–530.

B.Q. Liao, K. Xie, H.J. Lin, D. Bertoldo, Treatment of kraft evaporator condensate using a thermophilic submerged anaerobic membrane bioreactor, Water Sci. Technol. 61 (2010) 2177–2183.

Burhanettin Farizoglu, Suleyman Uzuner. The investigation of dairy industry wastewater treatment in a biological high performance membranesystem. Biochemical Engineering Journal. 2011, 57, 46– 54.

C.A. de Lemos Chernicharo, Biological Wastewater Treatment Series, Anaerobic Reactors, vol. 4, IWA Publishing, 2007. ISBN: 1843391643.

C.B. Ersu, S.K. Ong, Treatment of wastewater containing phenol using a tubular ceramic membrane bioreactor, Environ. Technol. 29 (2008) 225–234.

Carta-Escobar, F., Pereda-Marin, J., Alvarez-Mateos, P., Romero-Guzman, F., Duran Barrantes, 2005. Aerobic purification of dairy wastewater in continuous regime: part II: kinetic study of the organic matter removal in two reactor configurations. Biochem. Eng. J. 22, 117–124.

Chiu-Yue Lin, Anaerobic Digestion of Pesticide-Plant Wastewater. Biological Wastes 34 (1990) 215-226

D. Jeison (a), I. Diaz, J.B. Van Lier, Anaerobic membrane bioreactors: are membranes really necessary?, Electron J. Biotechnol. 11 (2008).

D. Jeison (b), W. Van Betuw, J.B. Van Lier, Feasibility of anaerobic membrane bioreactors for the treatment of wastewaters with particulate organic matter, Sep. Sci. Technol. 43 (2008) 3417–3431.

D. Jeison, J.B. van Lier, Cake formation and consolidation: main factors governing the applicable flux in anaerobic submerged membrane bioreactors (AnSMBR) treating acidified wastewaters, Sep. Purif. Technol. 56 (2007) 71–78.

D. Jeison, P. Telkamp, J.B. van Lier, Thermophilic sidestream anaerobic membrane bioreactors: the shear rate dilemma,Water Environ. Res. 81 (2009) 2372–2380.

D. Martinez-Sosa, B. Helmreich, T. Netter, S. Paris, F. Bischof, H. Horn, Anaerobic submerged membrane bioreactor (AnSMBR) for municipal wastewater treatment under mesophilic and psychrophilic temperature conditions, Bioresour. Technol. 102 (2011) 10377–10385.

D.W. Gao, T. Zhang, C.Y.Y. Tang, W.M. Wu, C.Y. Wong, Y.H. Lee, D.H. Yeh, C.S. Criddle, Membrane fouling in an anaerobic membrane bioreactor: differences in relative abundance of bacterial species in the membrane foulant layer and in suspension, J. Membr. Sci. 364 (2010) 331–338.

Danalewich, J.R., Papagiannis, T.G.; Belyea, R.L.; Tumbleson, M.E.; Raskin, L. Characterization of dairy waste streams, current treatment practices, and potential for biological nutrient removal. Water Res. 1998, 32 (12), 3555-3568.

Demirel B. Acidogenesis in two-phase anaerobic treatment of dairy wastewater. Ph.D. Thesis. Bogazici University, Istabul, Turkey; 2003.

Donkin, J. Bulking in aerobic biological systems treating dairy processing wastewaters. Int. J. Dairy Tech. 1997, 50, 67-72.

E. Jeong, H.W. Kim, J.Y. Nam, H.S. Shin, Enhancement of bioenergy production and effluent quality by integrating optimized acidification with submerged anaerobic membrane bioreactor, Bioresour. Technol. 101 (2010) S7–S12.

E. Kocadagistan, N. Topcub, Treatment investigation of the Erzurum City municipal wastewaters with anaerobic membrane bioreactors, Desalination 216 (2007) 367–376.

Eroglu V, Ozturk I, Demir I, Akca L, Alp K. Sequencing batch and hybrid anaerobic reactors treatment of dairy wastes. In: Proceedings of 46th Purdue industrial waste conference; 1991. p. 413–22.

F. Broens, D. Menne, I. Pothof, B. Blankert, H.D.W. Roesink, H. Futselaar, R.G.H. Lammertink, M. Wessling. Water hammer reduces fouling during natural water ultrafiltration. Water research 46 (2012) 1113-1120.

F. Carta-Escobar, J. Pereda-Marín, P. Álvarez-Mateos, F. Romero-Guzmán, M.M. Durán-Barrantes, F. Barriga-Mateos. Aerobic purification of dairy wastewater in continuous regime Part I: Analysis of the biodegradation process in two reactor configurations. Biochemical Engineering Journal, 2004, 21, 183–191.

F. Meng, B. Liao, S. Liang, F. Yang, H. Zhang, L. Song, Morphological visualization, componential characterization and microbiological identification of membrane fouling in membrane bioreactors (MBRs), J. Membr. Sci. 361 (2010) 1–14.

F. Meng, H. Zhang, F. Yang, L. Liu, Characterisation of cake layer in submerged membrane bioreactor, Environ. Sci. Technol. 41 (2007) 4065–4070.

G. Skouteris, D. Hermosilla, P. López, C. Negro, Á. Blanco, Anaerobic membrane bioreactors for wastewater treatment: A review, Chemical Engineering Journal 198–199 (2012) 138–148.

Gavala HN, Kopsinis H, Skiadas IV, Stamatelatou K, Lyberatos GL. Treatment of dairy wastewater using an upflow anaerobic sludge blanket reactor. J Agric Eng Res 1999, 73, 59–63.

H. Lin (a), J. Chen, F. Wang, L. Ding, H. Hong, Feasibility evaluation of submerged anaerobic membrane bioreactor for municipal secondary wastewater treatment, Desalination 280 (2011) 120–126.

H. Lin (b), B.-Q. Liao, J. Chen,W. Gao, L.Wang, F. Wang, X. Lu, New insights into membrane fouling in a submerged anaerobicmembrane bioreactor based on characterization of cake sludge and bulk sludge, Bioresour. Technol. 102 (2011) 2373–2379.

H. Park, K.-H. Choo, C.-H. Lee, Flux enhancement with powdered activated carbon addition in the membrane anaerobic bioreactor, Sep. Sci. Technol. 34 (1999) 2781–2792.

H.E. Grethlein, Anaerobic digestion and membrane separation of domestic wastewater, J. Water Pollut. Control Fed. 50 (1978) 754–763.

H.J. Lin, K. Xie, B. Mahendran, D.M. Bagley, K.T. Leung, S.N. Liss, B.Q. Liao, Sludge properties and their effects on membrane fouling in submerged anaerobic membrane bioreactors (SAnMBRs), Water Res. 43 (2009) 3827–3837.

H.-Y. Yu (a), Y.-J. Xie, M.-X. Hu, J.-L. Wang, S.-Y. Wang, Z.-K. Xu, Surface modification of polypropylene microporous membrane to improve its antifouling property in MBR: CO2 plasma treatment, J. Membr. Sci. 254 (2005) 219–227.

H.-Y. Yu (a), L.-Q. Liu, Z.-Q. Tang, M.-G. Yan, J.-S. Gu, X.-W. Wei, Surface modification of polypropylene microporous membrane to improve its antifouling characteristics in an SMBR: air plasma treatment, J. Membr. Sci. 311 (2008) 216–224.

H.-Y. Yu (b), M.-X. Hu, Z.-K. Xu, J.-L. Wang, S.-Y. Wang, Surface modification of polypropylene microporous membranes to improve their antifouling property in MBR: NH3 plasma treatment, Sep. Purif. Technol. 45 (2005) 8–15.

H.-Y. Yu (b), X.-C. He, L.-Q. Liu, J.-S. Gu, X.-W. Wei, Surface modification of poly(propylene) microporous membrane to improve its antifouling characteristics in an SMBR: O2 plasma treatment, Plasma Process. Polym. 5 (2008) 84–91.

H.Y. Yu, X.C. He, L.Q. Liu, J.S. Gu, X.W. Wei, Surface modification of polypropylene microporous membrane to improve its antifouling characteristics in an SMBR: N2 plasma treatment, Water Res. 41 (2007) 4703–4709.

Habets, L.H.A., de Vegt, A.L., 1991. Anaerobic treatment of bleached TMP and CTMP effluent in the Biopaq UASB system. Water Sci. Technol. 24 (3/4), 331-345

Haider M. Zwain, Siti Roshayu Hassan, Nastaein Qamaruz Zaman, Hamidi Abdul Aziz. The start-up performance of modified anaerobic baffled reactor (MABR) for the treatment of recycled paper mill wastewater. Journal of Environmental Chemical Engineering. 2013, 1, 61-64.

Hu, W.C., Thayanithy, K., Forster, C.F., 2002. A kinetic study of the anaerobic digestion of ice-cream wastewater. Process Biochem. 37, 965–971.

Hwang, S.; Hanse, C.L. Characterization of and bioproduction of short-chain organic acids from mixed dairy-processing wastewater. Trans. ASAE 1998, 41 (3), 795-802.

Hwang, S.H., Hansen, C.L., 1992. Performance of upflow anaerobic sludge blanket (UASB) reactor treating whey permeate. Trans. ASAE 35, 1665–1671.

I. Vyrides, D.C. Stuckey, Saline sewage treatment using a submerged anaerobic membrane reactor (SAMBR): effects of activated carbon addition and biogassparging time, Water Res. 43 (2009) 933–942.

I.S. Chang, K.H. Choo, C.H. Lee, U.H. Pek, U.C. Koh, S.W. Kim, J.H. Koh, Application of ceramic membrane as a pretreatment in anaerobic-digestion of alcohol-distillery wastes, J. Membr. Sci. 90 (1994) 131–139.

Ince, O. (a) Performance of a two-phase anaerobic digestion system when treating dairy wastewater. Wat. Res. 1998. 32 (9), 2707-2713.

Ince, O. (b) Potential energy production from anaerobic digestion of dairy wastewater. J. Environ. Sci. Health. 1998, A33 (6), 1219-1228.

J. Beltran, T. Gonzalez, J. Garcia, Kinetics of the biodegradation of green table olive wastewaters by aerobic and anaerobic treatments. Journal of Hazardous Materials 154 (2008) 839–845

J. Bohdziewicz, E. Neczaj, A. Kwarciak, Landfill leachate treatment by means of anaerobic membrane bioreactor, Desalination 221 (2008) 559–565.

J. Grundestam, D. Hellstrom, Wastewater treatment with anaerobic membrane bioreactor and reverse osmosis, Water Sci. Technol. 56 (2007) 211–217.

J. Ho, S. Sung, Anaerobic membrane bioreactor treatment of synthetic municipal wastewater at ambient temperature, Water Environ. Res. 81 (2009) 922–928.

J. Ho, S. Sung, Methanogenic activities in anaerobic membrane bioreactors (AnMBRs) treating synthetic municipal wastewater, Bioresour. Technol. 101 (2010) 2191–2196.

J. Kim, C.H. Lee, K.H. Choo, Control of struvite precipitation by selective removal of NH4+ with dialyzer/zeolite in an anaerobic membrane bioreactor, Appl. Microbiol. Biotechnol. 75 (2007) 187–193.

J. Kim, K. Kim, H. Ye, E. Lee, C. Shin, P.L. McCarty, J. Bae, Anaerobic fluidised bed membrane bioreactor for wastewater treatment, Environ. Sci. Technol. 45 (2011) 576–581.

J. Kochan, T. Wintgens, T. Melin, J. Wong, Characterization and filtration performance of coating-modified polymeric membranes used in membrane bioreactors, Chem. Pap. 63 (2009) 152–157.

J. Zhang, S.I. Padmasiri, M. Fitch, B. Norddahl, L. Raskin, E. Morgenroth, Influence of cleaning frequency and membrane history on fouling in an anaerobic membrane bioreactor, Desalination 207 (2007) 153–166.

J.A. Alvarez, I. Ruiz, M. Gomez, J. Presas, M. Soto. Start-up alternatives and performance of an UASB pilot plant treating diluted municipal wastewater at low temperature. Bioresource Technology, 2006, 97, 1640–1649.

J.O. Kim, J.T. Jung, Performance of membrane-coupled organic acid fermentor for the resources recovery form municipal sewage sludge, Water Sci. Technol. 55 (2007) 245–252.

J.W.J. Gao, H.J. Lin, K.T. Leung, B.Q. Liao, Influence of elevated pH shocks on the performance of a submerged anaerobic membrane bioreactor, Process Biochem. 45 (2010) 1279–1287.

Jai Prakash Kushwaha, Vimal Chandra Srivastava, Indra Deo Mall. Treatment of dairy wastewater by commercial activated carbon and bagasse fly ash: Parametric, kinetic and equilibrium modelling, disposal studies. Bioresource Technology, 2010, 101, 3474–3483.

Jutamas Kaewsuk, Worachat Thorasampan, Monthon Thanuttamavong, Gyu Tae Seo. Kinetic development and evaluation of membrane sequencing batch reactor (MSBR) with mixed cultures photosynthetic bacteria for dairy wastewater treatment. Journal of Environmental Management 91 (2010) 1161–1168.

K. Calderón, B. Rodelas, N. Cabirol, J. González-López, A. Noyola, Analysis of microbial communities developed on the fouling layers of a membranecoupled anaerobic bioreactor applied to wastewater treatment, Bioresour. Technol. 102 (2011) 4618–4627.

K. Stamatelatou, A. Kopsahelis, P.S. Blika, C.A. Paraskeva, G. Lyberatos, Anaerobic digestion of olive mill wastewater in a periodic anaerobic baffled reactor (PABR) followed by further effluent purification via membrane separation technologies, J. Chem. Technol. Biotechnol. 84 (2009) 909–917.

K. Wong, I. Xagoraraki, J. Wallace, W. Bickert, S. Srinivasan, J.B. Rose, Removal of viruses and indicators by anaerobic membrane bioreactor treating animal waste, J. Environ. Qual. 38 (2009) 1694–1699.

K. Xie, H.J. Lin, B. Mahendran, D.M. Bagley, K.T. Leung, S.N. Liss, B.Q. Liao, Performance and fouling characteristics of a submerged anaerobic membrane bioreactor for kraft evaporator condensate treatment, Environ. Technol. 31 (2010) 511–521.

K.C. Wijekoon, C. Visvanathan, A. Abeynayaka, Effect of organic loading rate on VFA production, organic matter removal and microbial activity of a two-stage thermophilic anaerobic membrane bioreactor, Bioresour. Technol. 102 (2011) 5353–5360.

K.-H. Choo, C.-H. Lee, Membrane fouling mechanisms in the membrane-coupled anaerobic bioreactor, Water Res. 30 (1996) 1771–1780.

K.-H. Choo, I.-J. Kang, S.-H. Yoon, H. Park, J.-H. Kim, S. Adiya, C.-H. Lee, Approaches to membrane fouling control in anaerobic membrane bioreactors, Water Sci. Technol. 41 (2000) 363–371.

K.V. Rajeshwari,M. Balakrishnan, A. Kansal, K. Lata, V.V.N. Kishore, State-of-the-art of anaerobic digestion technology for industrial wastewater treatment, Renew. Sustain. Energy Rev. 4 (2000) 135–156.

Kalogo, Y. Bouche J.H., Verstraete W., 2001. Physical and biological performance of self-inoculated UASB reactor treating raw domestic sewage. Journal of Environmental Engineering 127 (2), 179–183.

Kantawanichkul, S., 1990. Application of Hollow Fiber Membrane Bioreactor to Anaerobic Treatment of Oily Wastewater by Photosynthetic Bacteria: Rhodobacter sphaeroides. Ph.D. thesis. AIT, Bangkok, Thailand.

Kasapgil B, Anderson GK, Ince O. An investigation into the pretreatment of dairy wastewater prior to aerobic biological treatment. Water Sci Technol 1994, 29, 205–12.

Kasapgil B, Anderson GK, Ince O. An investigation into pre-treatment of dairy wastewater prior to aerobic biological treatment. Water Sci Technol 1994, 29(9), 205–12.

Kolarski R, Nyhuis G. The use of sequencing batch reactor technology for the treatment of high strength dairy processing waste. In: Proceedings of the 50th Purdue international waste conference; 1995. p. 485–94.

Koyuncu I, Turan M, Topacik D, Ates A. Application of low pressure nanofiltration membranes for the recovery and reuse of dairy industry effluents. Water Sci Technol 2000, 41(1), 213–21.

Lettinga G., de Man A., van der Last A.R.M., Wiegant W., van Knippenberg K., Frijns J., van Buuren J.C.L., 1993. Anaerobic treatment of domestic sewage and wastewater. Water Science and Technology 27 (9), 67–73.

M. Brockmann, C.F. Seyfried, Sludge activity and cross-flow microfiltration—a non-beneficial relationship, Water Sci. Technol. 34 (1996) 205–213.

M. Henze, Grady C:P.L., Gujer W., Maraias G.V.R. and Matsuo T. Activated sludge model N°1, report published by IAWPRC, London 1987.

M. Herrera-Robledo, J.M. Morgan-Sagastume, A. Noyola, Biofouling and pollutant removal during long-termoperation of an anaerobic membrane bioreactor treating municipal wastewater, Biofouling 26 (2010) 23–30.

M. Kanai, V. Ferre, S. Wakahara, T. Yamamoto, M. Moro, A novel combination of methane fermentation and MBR — Kubota Submerged Anaerobic Membrane Bioreactor process, Desalination 250 (2010) 964–967.

M. Xu, X. Wen, Z. Yu, Y. Li, X. Huang, A hybrid anaerobic membrane bioreactor coupled with on-line ultrasonic equipment for digestion of waste activated sludge, Bioresour. Technol. 102 (2011) 5617–5625.

Madigan M. T., Martinko J.M. and Parker J., Brock Biology of Microorganisms, 8th ed, (1997).

Malaspina F, Stante L, Cellamare CM, Tilche A. Cheese whey and cheese factory wastewater treatment with a biological anaerobic– aerobic process. Water Sci Technol 1995;32:59–72.

Malaspina, F.; Cellamare, C.M.; Stante, L.; Tilche, A. Anaerobic treatment of cheese whey with a downflow-upflow hybrid reactor. Biores. Technol. 1996, 55, 131-139.

Metcalf & Eddy, Wastewater Engineering: Treatment, disposal, reuse. McGraw-Hill International Editions. Third Edition,1991

Michael D. LaGrega, Philip L. Buckingham, Jeffrey C. Evans. Hazardous waste management - 2nd Edition. (2001)

Mirzaman Zamanzadeh, Wayne J. Parker, Yris Verastegui, Josh D. Neufeld, Biokinetic and molecular studies of methanogens in phased anaerobic digestion systems. Bioresource Technology 149 (2013) 318–326

Monroy OH, Vazquez FM, Derramadero JC, Guyot JP. Anaerobic– aerobic treatment of cheese wastewater with national technology in Mexico: the case of 'El Sauz'. Water Sci Technol 1995;32:149–56.

N. Brown, Methane dissolved in wastewater exiting UASB reactors: concentration measurement and methods for neutralisation, Department of Energy Technology, Royal Institute of Technology (KTH), Stockholm, Sweden, 2006.

Nakajima, F., Kamiko, N., Yamamoto, K., 1997. Organic wastewater treatment without greenhouse gas emission by photosynthetic bacteria. Water Sci. Technol. 35 (8), 285–291.

Nilsson, B., Strand, O., 1994. Evaporator condensate and caustic extraction liquor from a pulp factory treated with an anaerobic process. Water Sci. Technol. 29 (5-6), 399-407

Noparatnaraporn, N., Nishisawa, Y., Hayashi, M., Nagai, S., 1983. Single cell protein production from cassava starch by Rhodopseudomonas gelatinosa. In: Honda, R., 2005. Organic Wastewater Treatment by a Photosynthetic Pond Process for Tropical Regions and Population Dynamics of Photosynthetic Bacteria in the Pond. Ph.D. thesis. The University of Tokyo, Tokyo, Japan.

Noparatnaraporn, N., Trakulnaleumsai, S., Silveira, R.G., Nishizawa, Y., Nagai, S., 1987. SCP production by mixed culture of Rhodocyclus gelatinosa and Rhodobacter sphaeroides from cassava wastes. In: Honda, R., 2005. Organic Wastewater Treatment by a Photosynthetic Pond Process for Tropical Regions and Population Dynamics of Photosynthetic Bacteria in the Pond. Ph.D. thesis. The University of Tokyo, Tokyo, Japan.

Ozturk I, Eroglu V, Ubay G, Demir I. Hybrid upflow anaerobic sludge blanket reactor (HUASBR) treatment of dairy effluents. Water Sci Technol 1993;28:77–85.

P. Le-Clech, V. Chen, T.A.G. Fane, Fouling in membrane bioreactors used in wastewater treatment, J. Membr. Sci. 284 (2006) 17–53.

P. Weiland, Biogas production: current state and perspectives, Appl. Microbiol. Biotechnol. 85 (2010) 849–860.

P.J. Van Zyl, M.C. Wentzel, G.A. Ekama, K.J. Riedel, Design and start-up of a high rate anaerobic membrane bioreactor for the treatment of a low pH, highstrength, dissolved organic wastewater, Water Sci. Technol. 57 (2008) 291–295.

P.M. Sutton, H. Melcer, O.J. Schraa, A.P. Tonga, Treating municipal wastewater with the goal of resource recovery, Water Sci. Technol. 63 (2010) 25–31.

P.R. Bérubé, E.R. Hall, P.M. Sutton, Parameters governing permeate flux in an anaerobic membrane bioreactor treating low-strength municipal wastewaters: a literature review, Water Environ. Res. 78 (2006) 887–896.

R.W. Baker, Membrane Technology and Applications,McGraw-Hill,NewYork, 2000.

S. Malamis, E. Katsou, D. Chazilias, M. Loizidou, Investigation of Cr(III) removal from wastewater with the use of MBR combined with low-cost additives, J. Membr. Sci. 333 (2009) 12–19.

S. Zhang, Y. Qu, Y. Liu, F. Yang, X. Zhang, K. Furukawa, Y. Yamada, Experimental study of domestic sewage treatment with a metal membrane bioreactor, Desalination 177 (2005) 83–93.

S.F. Aquino, A.Y. Hu, A. Akram, D.C. Stuckey, Characterization of dissolved compounds in submerged anaerobic membrane bioreactors (SAMBRs), J. Chem. Technol. Biotechnol. 81 (2006) 1894–1904.

S.H. Baek, K.R. Pagilla, Aerobic and anaerobic membrane bioreactors for municipal wastewater treatment, Water Environ. Res. 78 (2006) 133–140.

S.H. Baek, K.R. Pagilla, H.J. Kim, Lab-scale study of an anaerobic membrane bioreactor (AnMBR) for dilute municipal wastewater treatment, Biotechnol. Bioproc. Eng. 15 (2010) 704–708.

S.-R. Chae, S.Wang, Z.D. Hendren,M.R.Wiesner, Y.Watanabe, C.K. Gunsch, Effects of fullerene nanoparticles on Escherichia coli K12 respiratory activity in aqueous suspension and potential use for membrane biofouling control, J. Membr. Sci. 329 (2009) 68–74.

Samkutty, P.J.; Gough, R.H. Filtration treatment of dairy processing wastewater. J. Environ. Sci. Health. 2002, A37 (2), 195-199.

Somiya, I., Kuriyama, A., Kamaish, I.H., Ono, Y., 1988. The development of anaerobic microbial reactor by purple nonsulfur bacteria for domestic wastewater treatment. In: Present Paper at the Second IAWPRC Asian Conference on Water Pollution Control, Bangkok, Thailand.

Sparling, G.P.; Schipper, L.A.; Russel, J.M. Changes in soil properties after application of dairy factory effluent to New Zealand volcanic ash and pumice soils. Aust. J. Soil. Res. 2001, 39, 505-518.

Strydom, J.P.; Britz, T.J.; Mostert, J.F. Two-phase anaerobic digestion of three different dairy effluents using a hybrid bioreactor. Water SA 1997, 23, 151-156.

T. Imasaka, N. Kanekuni, H. So, S. Yoshino, Cross-flow filtration of methane fermentation broth by ceramic membranes, J. Ferment. Bioeng. 68 (1989) 200–206.

T. Mohammadi, S.S. Madaeni, M.K. Moghadam, Investigation of membrane fouling, Desalination 153 (2003) 155–160.

T. Wang, H. Zhang, F. Yang, S. Liu, Z. Fu, H. Chen, Start-up of the Anammox process from conventional activated sludge in a membrane bioreactor, Bioresour. Technol. 100 (2009) 2501–2506.

T.T. Teng, T.S. Wong, S.A. Ong, M Norhashimah, M Rafatullah. Start-up operation of anaerobic degradation process for palm oil mill effluent in anaerobic bench scale reactor (ABSR). 2013, 18, 442-450.

Tjoon Tow Teng, Tee-Shian Wong, Soon-An Ong, M. Norhashimah, M. Rafatullah, Start-up operation of anaerobic degradation process for palm oil mill effluent in anaerobic bench scale reactor (ABSR), Environmental Sciences 18 (2013) 442-450.

Torrijos, M.; Vuitton, V.; Moletta, R. The SBR process: an efficient and economic solution for the treatment of wastewater at small cheese making dairies in the Jura Mountains. Wat. Sci. Technol. 2001, 43, 373-380.

Udo Wiesmann, In Su Choi, Eva-Maria Dombrowski. Fundamentals of Biological Wastewater Treatment. WILEY-VCH 2077

V. B. Brião, C. R. Granhen Tavares. Effluent generation by the dairy industry: preventive attitudes and opportunities. Brazilian Journal of Chemical Engineering. 2007, 24, 487 – 497.

Van den Berg L, Kennedy KJ. Dairy waste treatment with anaerobic stationary fixed film reactors. In: Malina JF, Pohland FG, editors. Design of anaerobic processes for the treatment of industrial and municipal wastes. Pennsylvania: Technomic Publishing Company; 1992. p. 89–96.

Vera Mota. Performance results of the treatment of stillage using two-stage anaerobic digestion coupled to membrane filtration at different operating conditions. www.iwawaterwiki.org. (2013)

W. Charles, L. Walker, R. Cord-Ruwisch. Effect of pre-aeration and inoculum on the start-up of batch thermophilic anaerobic digestion of municipal solid waste. Bioresource Technology, 2009, 100, 2329–2335.

W. Fuchs, H. Binder, G. Mavrias, R. Braun, Anaerobic treatment of wastewater with high organic content using a stirred tank reactor coupled with a membrane filtration unit, Water Res. 37 (2003) 902–908.

W.J. Gao, K.T. Leung, W.S. Qin, B.Q. Liao, Effects of temperature and temperature shock on the performance and microbial community structure of a submerged anaerobic membrane bioreactor, Bioresource Technology. 102 (2011) 8733–8740.

W.J.J. Gao, H.J. Lin, K.T. Leung, B.Q. Liao, Influence of elevated pH shocks on the performance of a submerged anaerobic membrane bioreactor, Process Biochem. 45 (2010) 1279–1287.

W.R. Ghyoot, W.H. Verstraete, Coupling membrane filtration to anaerobic primary sludge digestion, Environ. Technol. 18 (1997) 569–580.

Wang & Howard. "Handbook of Industrial and Hazardous Wastes Treatment" 2004.

X. Wen, P. Sui, X. Huang, Exerting ultrasound to control the membrane fouling in filtration of anaerobic activated sludge—mechanism and membrane damage, Water Sci. Technol. 57 (2008) 773–779.

Xiaoxia Li, Xiaochen Liu, Shihan Wu, Aamir Rasool, Jiane Zuo, Chun Li, Guiyan Liu. Microbial diversity and community distribution in different functional zones of continuous aerobic–anaerobic coupled process for sludge in situ reduction. Chemical Engineering Journal 257 (2014) 74–81

Y. An, Z. Wang, Z. Wu, D. Yang, Q. Zhou, Characterization of membrane foulants in an anaerobic non-wooven fabric membrane bioreactor for municipal wastewater treatment, Chem. Eng. J. 155 (2009) 709–715.

Y. Chen, J.J. Cheng, K.S. Creamer, Inhibition of anaerobic digestion process: a review, Bioresour. Technol. 99 (2008) 4044–4064.

Y.J. Chan, M.F. Chong, C.L. Law, D.G. Hasell, A review on anaerobic–aerobic treatment of industrial and municipal wastewater, Chem. Eng. J. 155 (2009) 1–18.

Yee-Shian Wong, Tjoon-Tow Teng, Soon-An Ong, M. Norhashimah, M. Rafatullah, Jing-Yong Leong. Methane gas production from palm oil wastewater—An anaerobic methanogenic degradation process in continuous stirrer suspended closed anaerobic reactor. Journal of the Taiwan Institute of Chemical Engineers 45 (2014) 896–900.

Yi Jing Chan, Mei Fong Chong, Chung Lim Law. An integrated anaerobic–aerobic bioreactor (IAAB) for the treatment of palm oil mill effluent (POME): Start-up and steady state performance. Process Biochemistry. 2012, 47, 485–495.

Yu, Y., Hansen, C.L., Hwang, S., 2002. Biokinetics in acidogenesis of highly suspended organic wastewater by adenosine 5-triphosphate analysis. Biotechnol. Bioeng. 78, 147–156.

Z. Huang, S.L. Ong, H.Y. Ng, Feasibility of submerged anaerobic membrane bioreactor (SAMBR) for treatment of low-strength wastewater, Water Sci. Technol. 58 (2008) 1925–1931.

Z. Huang, S.L. Ong, H.Y. Ng, Submerged anaerobic membrane bioreactor for low-strength wastewater treatment: effect of HRT and SRT on treatment performance and membrane fouling, Water Res. 45 (2011) 705–713.

Z. Ying, G. Ping, Effect of powdered activated carbon dosage on retarding membrane fouling in MBR, Sep. Purif. Technol. 52 (2006) 154–160.

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